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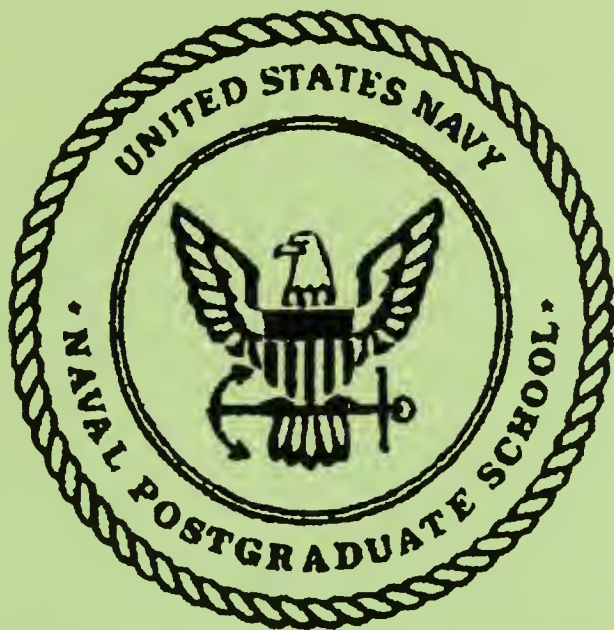






# **NAVAL POSTGRADUATE SCHOOL**

## **Monterey, California**



## **THESIS**

### **EXPERIMENTAL INQUIRIES INTO COLLECTIVE SEA STATE MODES IN DEEP WATER SURFACE GRAVITY WAVES**

by

Richard T. Lawrence

December, 1992

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**EXPERIMENTAL INQUIRIES INTO COLLECTIVE SEA STATE MODES  
IN DEEP WATER SURFACE GRAVITY WAVES**

by

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Submitted in partial fulfillment of the requirements for the degree of  
**MASTER OF SCIENCE IN ENGINEERING ACOUSTICS**

from the

**NAVAL POSTGRADUATE SCHOOL**

December 1992

## ABSTRACT

An experiment designed to find collective sea state modes in deep water surface gravity waves was performed. The experiment was conducted in a large water tank with fans to create wind a driven background sea state. This background sea state may be more precisely referred to as a condition of wave turbulence. The background sea state was perturbed with an additional burst of waves created at one end of the tank by a computer controlled mechanical paddle. Different wind speeds and input burst waveforms were used. The wave height was measured with a four wire probe, with integrated circuit implementation. Data acquisition, manipulation, and averaging were automated. The probable collective mode can be seen in spectral density versus time images as a nondispersive decrease in background spectral density. It was estimated that this decrease in spectral density propagated independently of the input wave burst by examining its arrival time relative to burst energy arrival time for different probe to paddle distances. More importantly, it was determined that the propagation speed was a function of the background spectral peak frequency. Additionally, input burst energy at frequencies above the background spectral peak was not observed to propagate.

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I must also thank my wife who supported me while she was here, and was pioneering enough in spirit to leave early for the East Coast. Thanks to my two daughters, Chelsea and Amelia who made every effort to make my time at home a distinct diversion from work.

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## I. INTRODUCTION

Waves on water are as natural and common as they are complex. Despite the enormous Naval and Oceanographic importance of waves on the ocean, the subject has been explored primarily phenomenologically. While some aspects of surface gravity wave propagation have been investigated analytically, real, highly nonlinear phenomena such as wave generation by wind, wave breaking, and the aggregate interaction of waves on the sea await complete analysis. This thesis represents an effort to study the collective behavior of waves in a controlled laboratory environment. The impetus for this research is a paper by Larraza, Garrett, and Putterman (1990), which predicts a propagating mode of surface gravity waves on water analogous to second sound in liquid Helium-4 ( $\text{He}^4$ ). The mode is predicted to arise as a result of the collective, nonlinear interactions of waves in a random sea, and appears as a propagating change in wave height energy of the sea. As an analogy, water waves take on a particulate nature, and are seen to interact somewhat similarly to particles in a gas that collide with each other, exchanging momentum. In terms of real ocean observations, the new mode would be seen as a propagating increase in sea state possibly resulting from a distant short-lived storm or front. Rather than each wave of the storm propagating independently, leading to an outwardly spreading circular area of higher sea state, interactions between the waves should create a collective sea state mode which would *propagate outwardly* as a ring. Again in analogy, the wave of waves propagates as *sound*, and it is this mode for which the experiment is designed.

## II. THEORY

### A. DISPERSION RELATION

The dispersion relation for deep water gravity waves is given by

$$\omega^2 = gk,$$

where  $\omega$  is the angular frequency of the wave,  $g$  is the acceleration due to gravity, and  $k$  is the wave number. This approximate relation is valid for frequencies less than 13.6 Hertz, and in water more than one reduced wavelength  $1/k$  deep. Thus a practical lower frequency limit in the tank used for the experiment is 0.4 Hertz. The group velocity  $v_g$  is obtained from the dispersion relation by differentiation:

$$v_g = \frac{d\omega}{dk} = \frac{1}{2} \sqrt{g/k},$$

and substituting for  $k$  from the dispersion relation gives

$$v_g = \frac{1}{2} \frac{g}{\omega}.$$

In order to calculate the time of flight for pulse of waves over a fixed distance  $d$ , as a function of frequency, the simple time-distance relationship is used:

$$T = \frac{d}{v_g} = \frac{4\pi fd}{g}$$

where the frequency,  $f$  is now expressed in Hertz. The time of flight  $T$  is thus a linear function of frequency. When the power spectrum of a wideband burst of waves is

measured as a function of time some distance away the maximum wave energy will be a diagonal straight line.

## B. SPECTRA

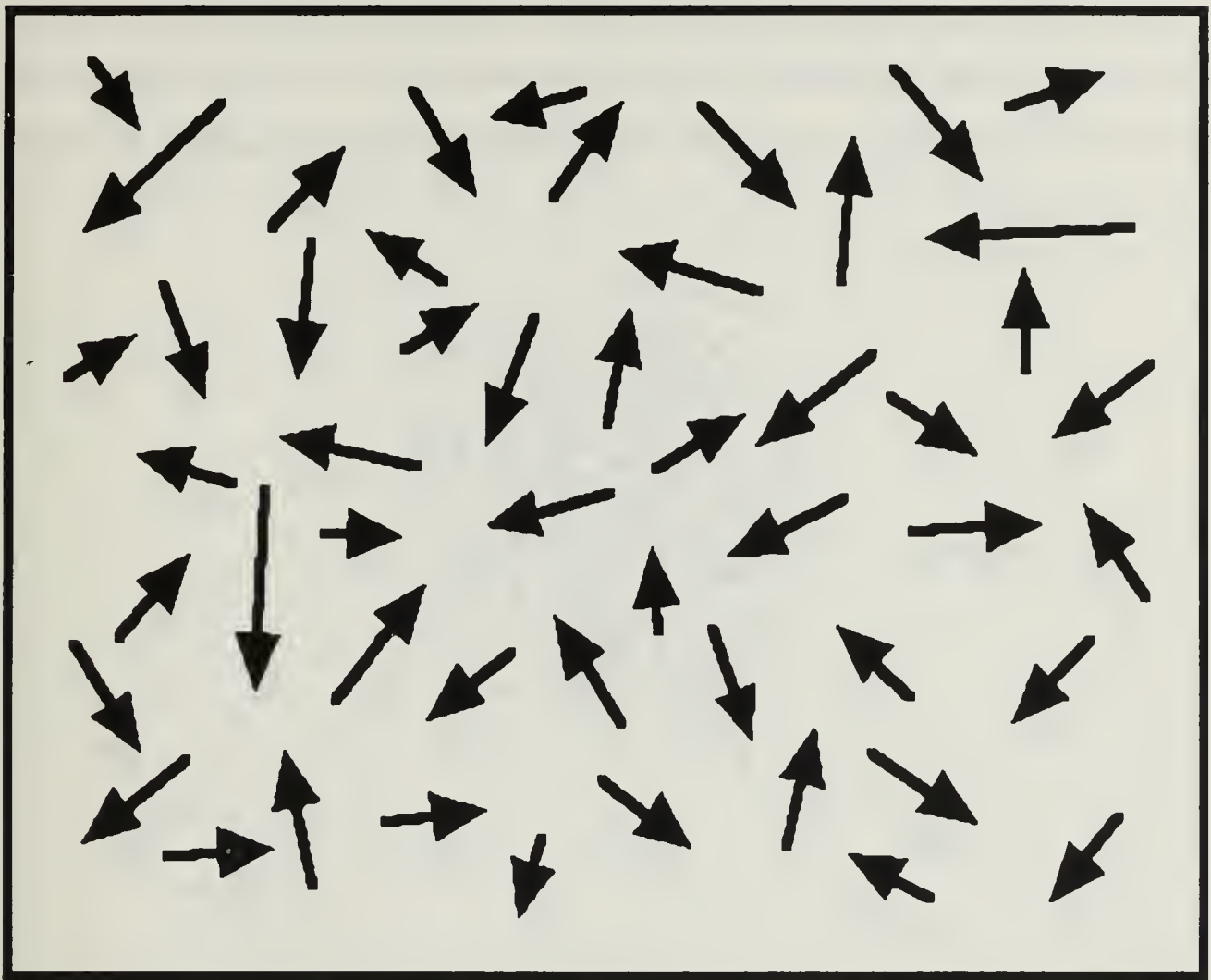
Winds over water produce frequency spectra as a function of the wind velocity and distance over which the wind blows (fetch). While the whole water surface can be thought of as a random system, the wavelengths present obey an approximate power law (Phillips, 1977). The correlation between wind velocity and spectral peak can be made by relating wind velocity to the phase velocity of the waves (Miles, 1962). For frequencies higher than the spectral peak, empirical studies done on a real ocean have shown the power spectrum to initially follow an  $\omega^{-4}$  dependence, and at higher frequencies, an  $\omega^{-5}$  dependence (Forristall, 1981). These are precisely the power laws predicted by simple scaling arguments for weak and saturated wave turbulence, respectively (Larrazza and Putterman, 1987; and Larrazza, 1985). In this laboratory, wind is produced by fans located above water in a large tank, Yarber's previous results (1992), show that this particular, artificially produced spectrum approximated an  $\omega^{-(6\pm1)}$  power law.

## C. COLLECTIVE MODES

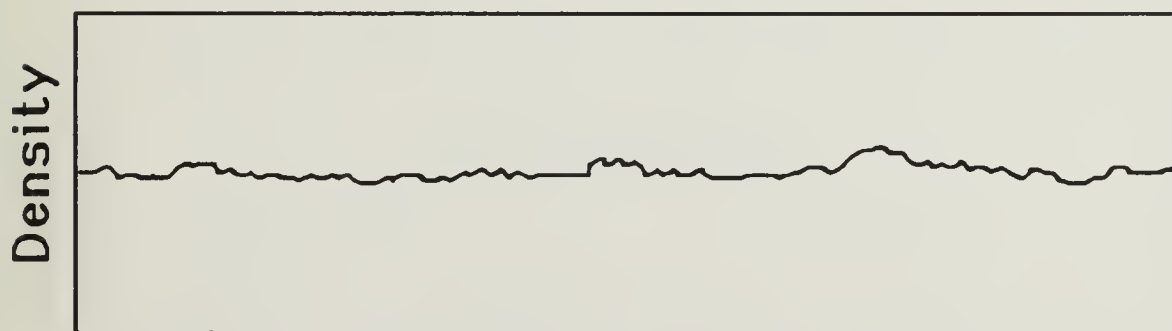
The term "collective mode," in general, refers to the coherent response of an entire system to a disturbance. Simple excitation of the water surface and its resulting wave motion is an example of the most basic, elementary mode, and is a collective mode of the water particles. In the case of deep water surface gravity waves, a new collective mode comprised of these simple elementary waves has been predicted to exist (Larrazza, 1992). It is a propagating variation in the background power spectra of a random sea in response to a localized increase in wave height energy--*a wave of sea state*. In the following, a loose analogy to sound in gases is made by considering the individual, elementary gravity waves to be particles of a gas.

To begin the thought experiment, consider a two dimensional box filled with particles of random speeds and directions, as depicted in Figure 2.1 , where each arrow represents an individual particle with its respective velocity and direction. The density as a function of position across an area through the center of the box will be approximately constant for the most part and this is depicted below the box. This display is similar for each subsequent case in the development.





a. Box of Particles Distributed Randomly in Space and Velocity

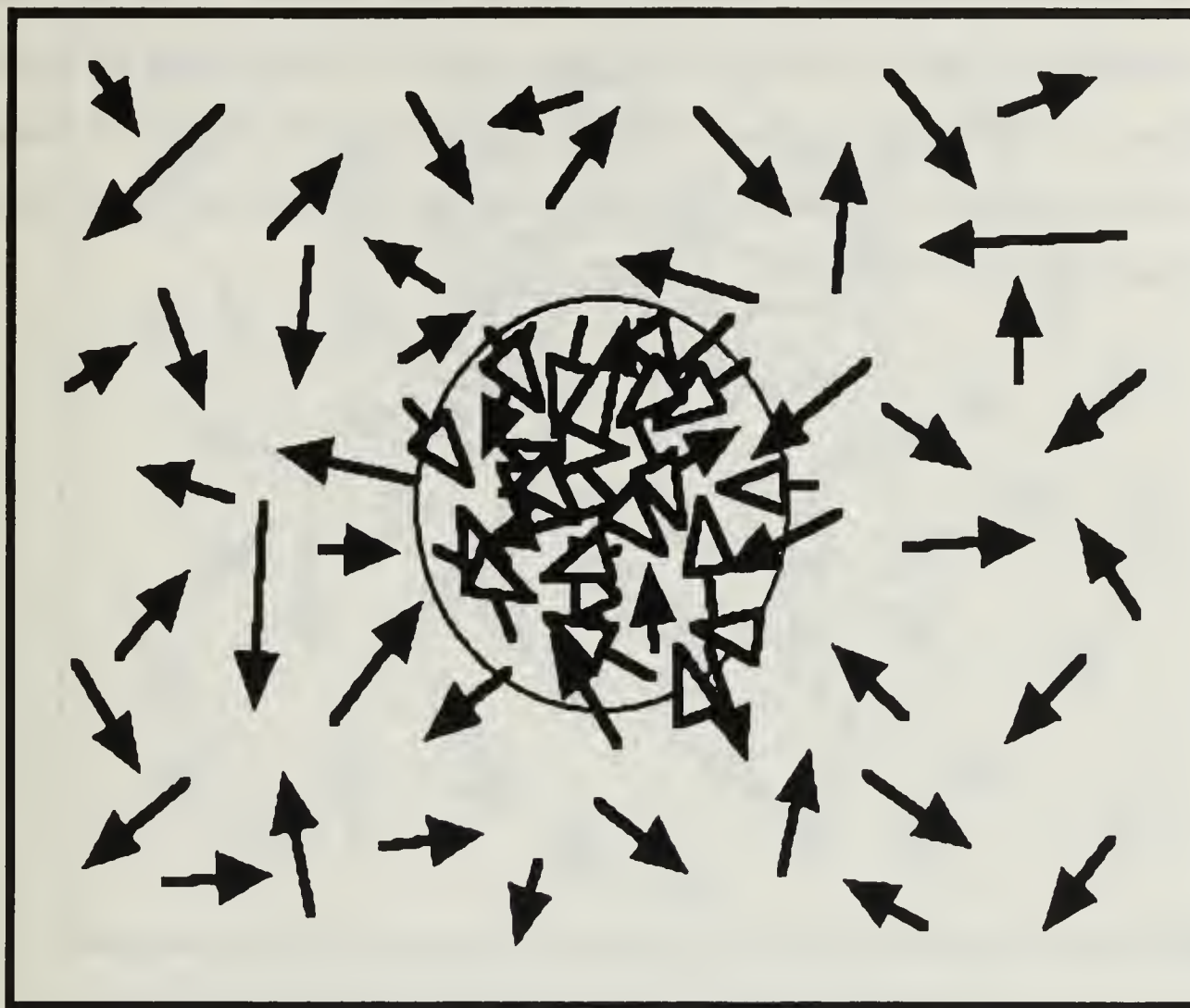


b. Even Spatial Density Distribution .

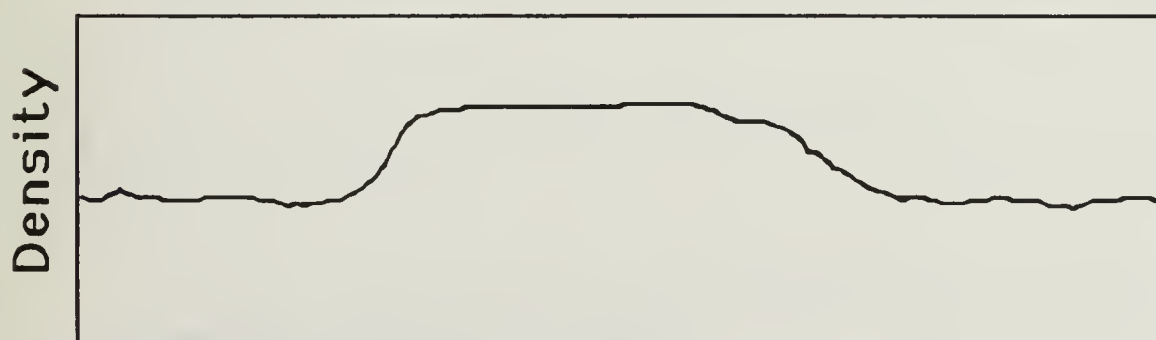
Figure 2.1 Illustration of Particles in a Box and Respective Density Distribution

Now consider the effects of adding a number of particles at the center of the box so that the addition does not initially disturb the original particles. These new particles are instantaneously transported into the box. The result at the moment the particles are added is shown in Figure 2.2.





a. Added Particles Within Bounds of Drawn Circle

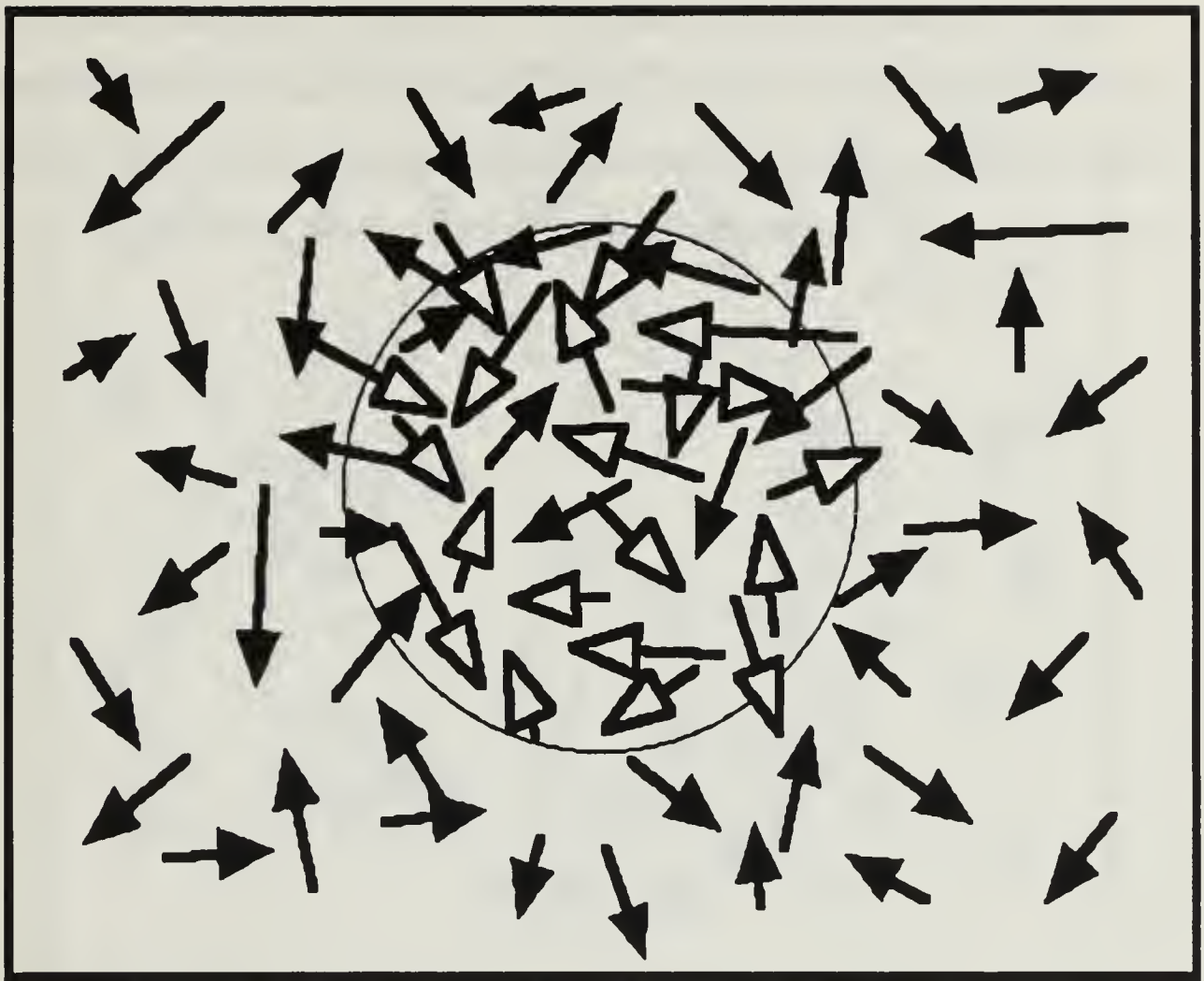


b. Locally High Distribution of Density

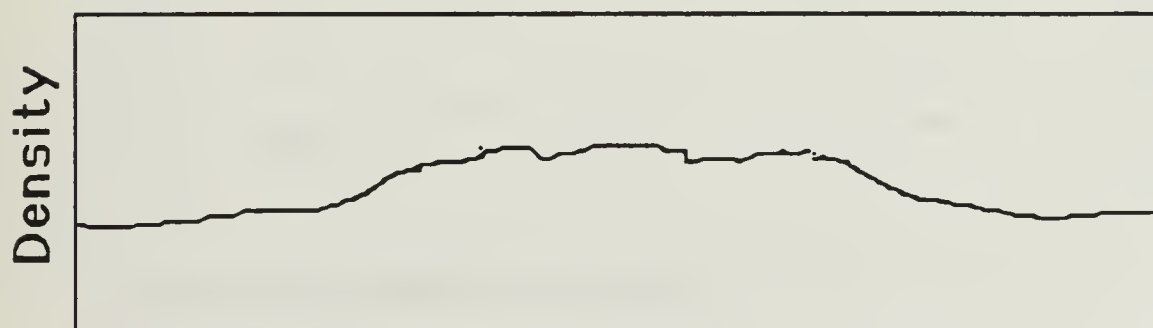
Figure 2.2 Illustration of Particles Added

The added particles are those arrows with hollow heads, and the ring drawn indicates the region where they were added. For the same cross section taken before, the density will acquire a localized increase as shown. The question is how this density will change with time. It may be reasonably expected that this local increase will spread out as indicated in the next illustration.





a. Added Particles Spreading as Shown by Expanded Circle



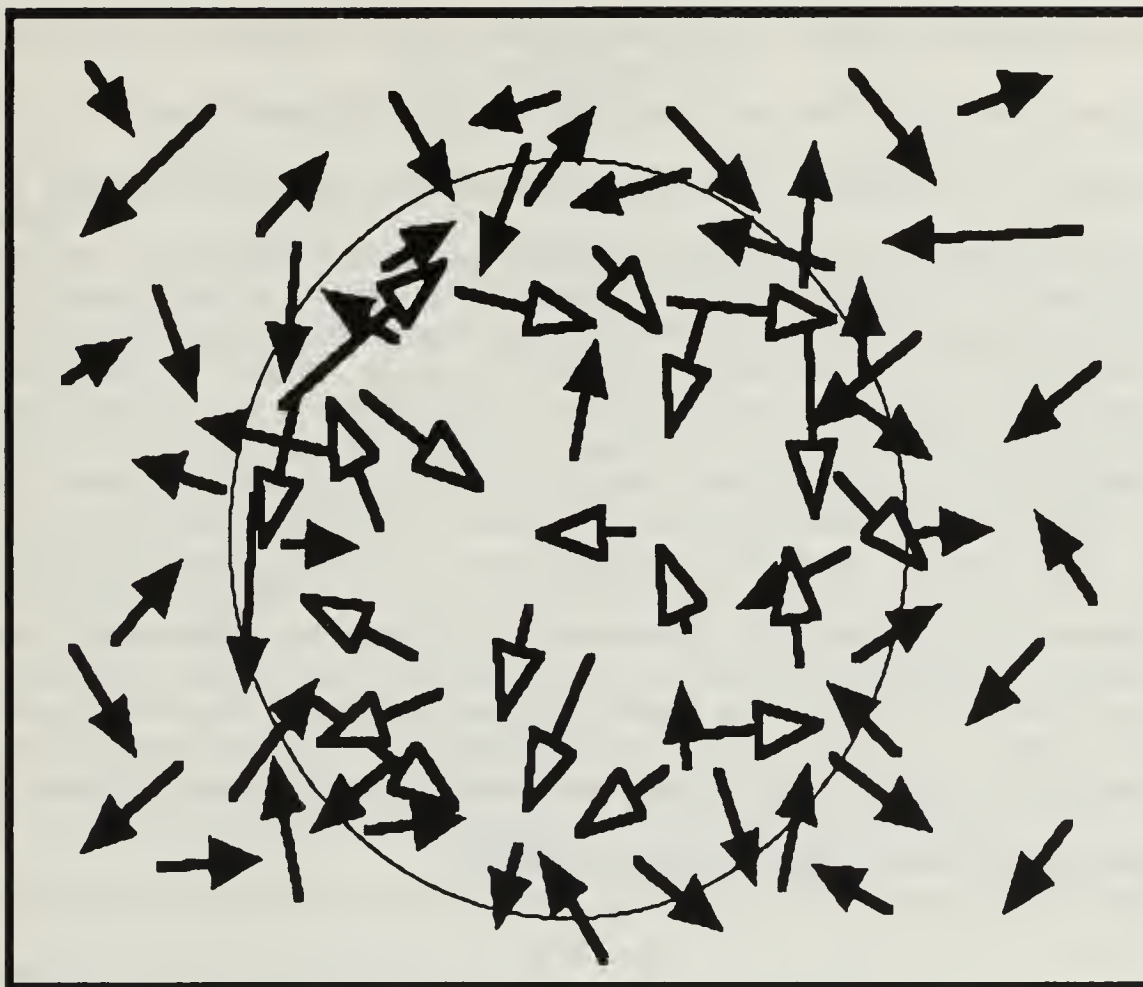
b. Spreading Distribution of Density

Figure 2.3 Illustration of Spreading

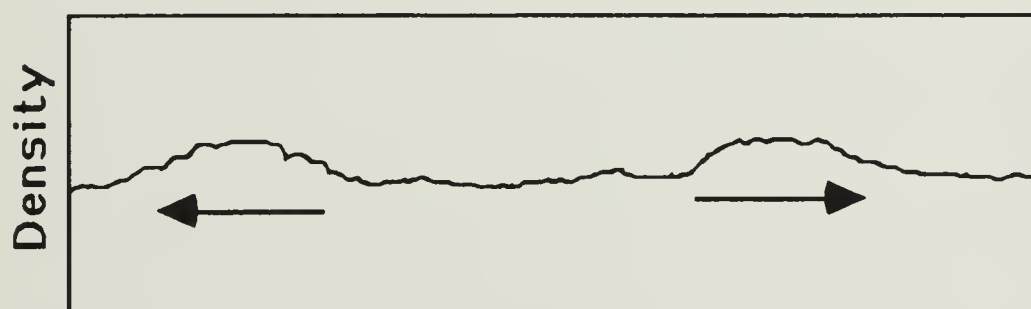


As any acoustician knows, this description is incorrect. In this situation sound occurs. Sound in air is made up of changes in density caused by volume velocities and pressure gradients, which propagate via interactions between molecules of air that vary considerably in direction and speed. The actual phenomena (sound) is shown in Figure 2.4.





a. Ring Illustrating Propagating Increased Density



b. Propagating Distribution of Density

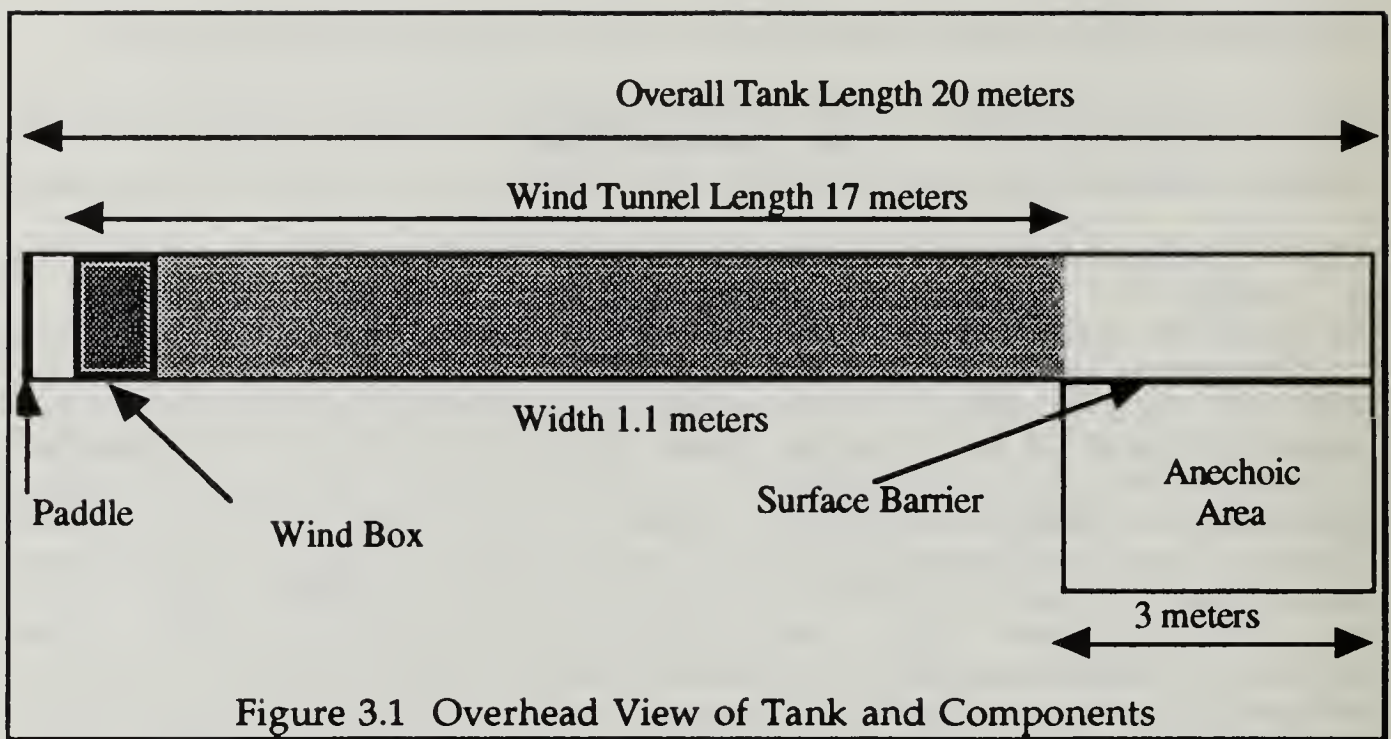
Figure 2.4 Propagation of Sound

Here the increase in density around the ring represents sound, and the density plot, shows two localized regions of increased density which propagate outward. Now the analogy can be made to waves on water. Each wave is represented by an arrow in Figures 2.1 through 2.4. In Figure 2.1 the situation is analogous to a full swimming pool or a confused sea where there is little or no coherence of the individual waves, and there is an uniform spatial distribution throughout the pool or region. A system of waves in this fully developed condition is called "wave turbulent." In Figure 2.4, for the case of waves on water, the region of increased density along the ring is an increase in sea state--a wave of waves. This wave of waves is the collective mode sought. Most importantly, it is dispersionless just as sound in air. This means that all frequency components propagate at the same speed. Additionally, this speed is also proportional to the average speed of the waves which comprise the background sea state, just as the speed of sound in air is proportional to the average speed of the air molecules.

### **III. APPARATUS**

#### **A. TANK**

The primary apparatus for this experiment is a covered water tank 20 meters long, 1.1 meters wide, and 1.5 meters average depth. Near one end are five  $\frac{3}{4}$  horsepower centrifugal fans mounted on a large wooden frame above the water. There is a gap of 0.34 meters between the back of the wind box and the tank wall where a paddle is placed. At the opposite end the tank opens up to an acoustically anechoic volume, 3 meters by 3 meters in area and 2.8 meters deep. However, most of this volume was isolated by a surface barrier (a two by ten inch board) to create a usable surface channel of 20 by 1.1 meters. The wind tunnel does not extend over this expanded area. The nominal distance between the ceiling of the wind tunnel and the water surface is 0.15 meters. An illustration as viewed from above, and not to scale, is shown below:



The surface of the water was cleaned by a swimming pool skimming filter installed in the expanded area of the tank. A pump, which requires priming, draws a suction on the surface filter, and discharges through a T-valve to a sand filter that removes particulates from the water. The filtered water is carried back to the opposite end of the tank by piping along the side of the tank. The T-valve on the discharge side of the pump can be used to drain the tank and control the water level by directing the discharge to the building sewage line.

The five  $\frac{3}{4}$  horsepower centrifugal fans provide a range of discreetly variable wind velocities for the experiment. The fans are mounted so that they discharge vertically down through a large wooden box (wind box). Baffles near the bottom of the box deflect the air stream horizontally as it exits the wind box. The air stream is not completely horizontal as it exits the wind box, and creates a small impact area directly under the wind box. A relatively quiescent area remains between the wind box and the paddle. The fans are electrically switched in three groups with the first group consisting of a single fan, and the



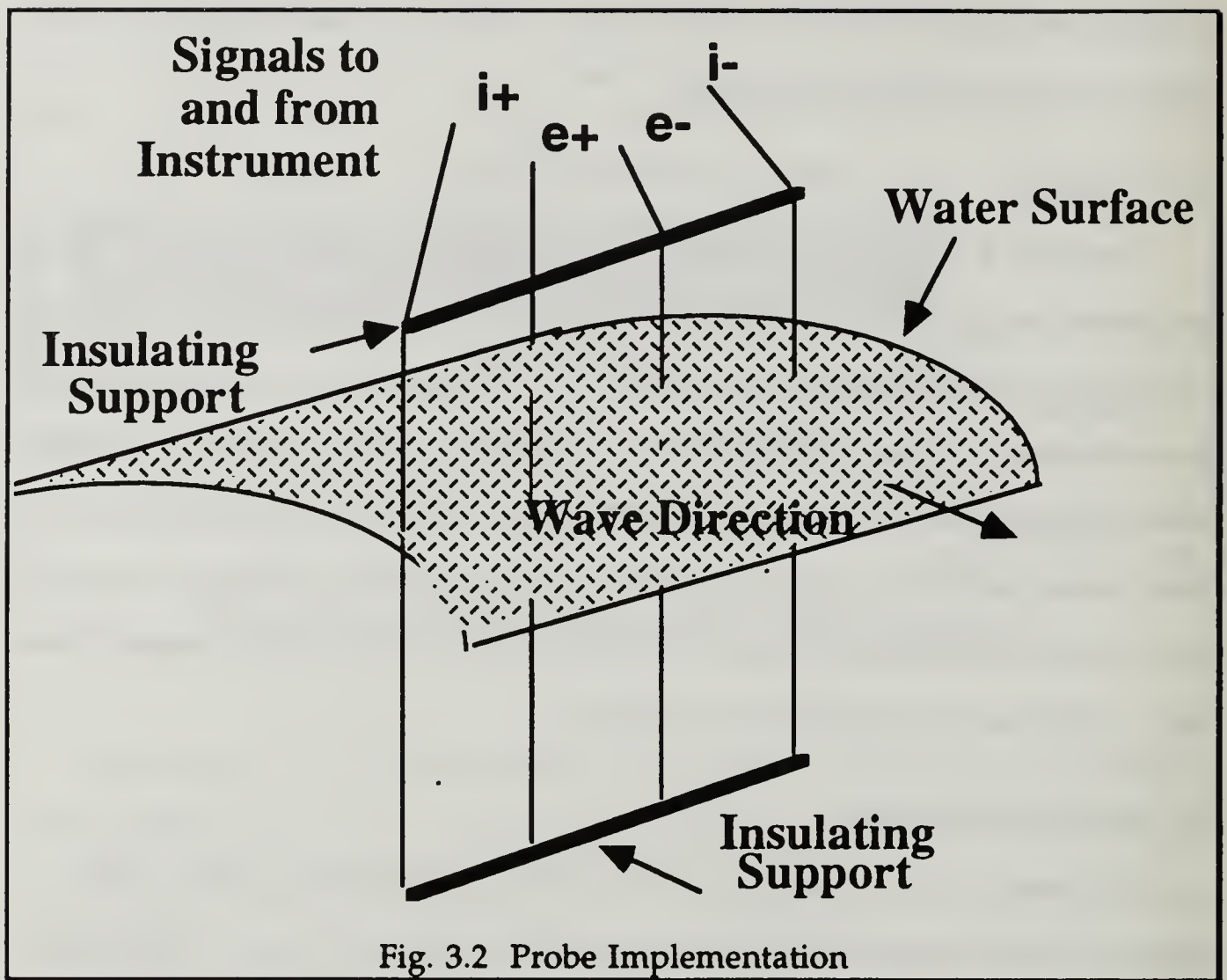
remaining two groups consisting of two fans each. Used in different combinations, a wide range of wind velocities can be obtained.

## **B. PADDLE**

The paddle is the controllable source of waves, and consists of a sheet of plywood just less than the width of the tank, 0.75 meters deep, and mounted on its bottom edge to a pair of vertical two by four inch beams clamped to the tank wall. The top edge of the paddle was mechanically driven horizontally by a linear motor, and the outgoing waves are directed down the tank. The motor, an APS Model 113 ELECTRO-SEIS Shaker, was linked to the paddle with a 1/2-inch threaded rod with ball joints at both ends. In turn, the motor was electrically driven by an APS Model 114 Power Amplifier which amplified the input analog waveforms generated by computer.

## **C. WAVE DETECTION**

The sensing of water height by four wire probe is addressed by Yarber (1992). A slightly different electronic circuit was implemented in this experiment. A self-contained wave staff and electronics unit was made from commercially available integrated analog circuits. The wave staff itself, made by Yarber, consists of four inline parallel wires placed vertically into the water. The outer two wires are driven by alternating current sources of opposite polarity. Each of the two inner wires sense a voltage proportional to the complex impedance between them. The illustration in Figure 3.2 below shows the implementation used. The detector is normally placed so that the plane formed by the probe wires is perpendicular to the wave direction.



The complete wiring diagram for the instrument is shown in Figure 3.3. Its output is an analog voltage signal proportional to the wave height. It operates on a lock-in amplifier principle using an external input AC signal as a carrier signal, and uses an analog divider chip to take the reciprocal of the sensed voltage before output. The external 10 kHz 3.5 Volt peak signal originated from an HP 2561 Dynamic Signal Analyzer. The two LF-345 opamps operate in push-pull fashion to drive the current wires  $i+$  and  $i-$  of the probe. The voltage difference between the inner wires ( $e+ - e-$ ) is a direct measurement of the impedance of the water between the wires, and is amplified by the AMP-01 Low Noise Precision Instrumentation Amplifier with a gain of 100. The AD 633 Analog Multiplier

demodulates the incoming voltage signal by multiplying it against the external AC input signal. The signal is then passed to the AD 734 High Speed Multiplier/Divider which takes the reciprocal of the signal to arrive at an admittance which is proportional to the water height. Gain and Offset adjustments can be made to the circuit by trimming potentiometers connected to the AD 734 that can be used to optimize or calibrate the output signal. A rough static calibration was performed on the instrument, and its sensitivity found to be 0.80 Volts per centimeter.

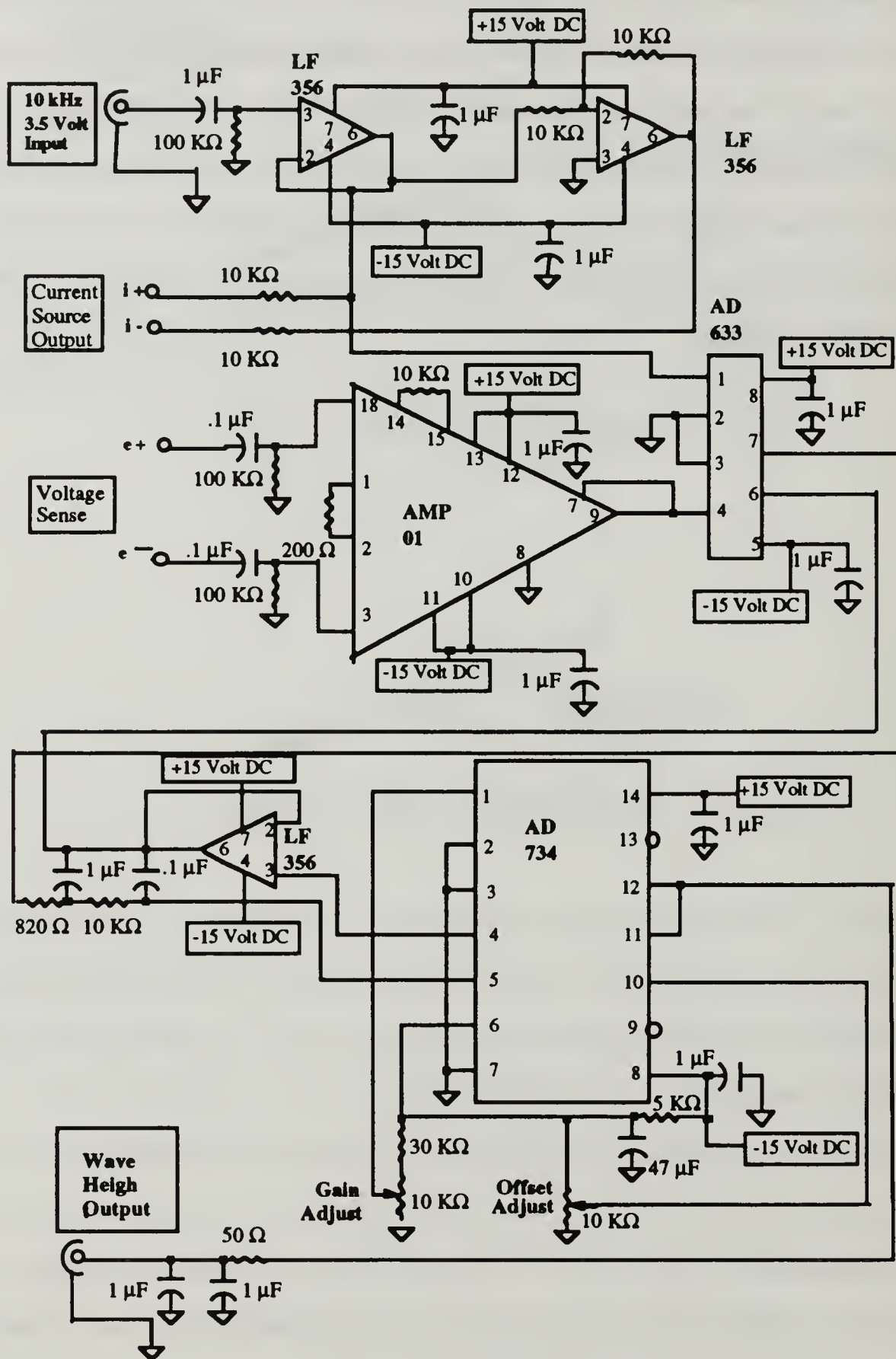


Figure 3.3 Complete Wiring Diagram for Wave Height Detector Circuit

A Kepco MPS-60 Multiple Output Power Supply supplies positive and negative fifteen volt DC power to the circuit. The output of the circuit is carried by BNC cable to a Macintosh IIfx computer where it is digitized. The external 10 kHz input signal from the HP 3562 is also carried by BNC cable.



## **IV. EXPERIMENT**

### **A. OVERVIEW**

The object of this experiment is to measure the response of a system of random deep water gravity waves to a spatial perturbation. The background sea of waves, analogous to particles in a gas, is created by wind. The perturbation in sea state, analogous to the added particles, is created by waves generated by a paddle. The wave height is measured, processed, and ultimately yields information about how the system responds. For an integrated view of the experiment, the illustration of Figure 4.1 below shows how each component functions as part of the whole.

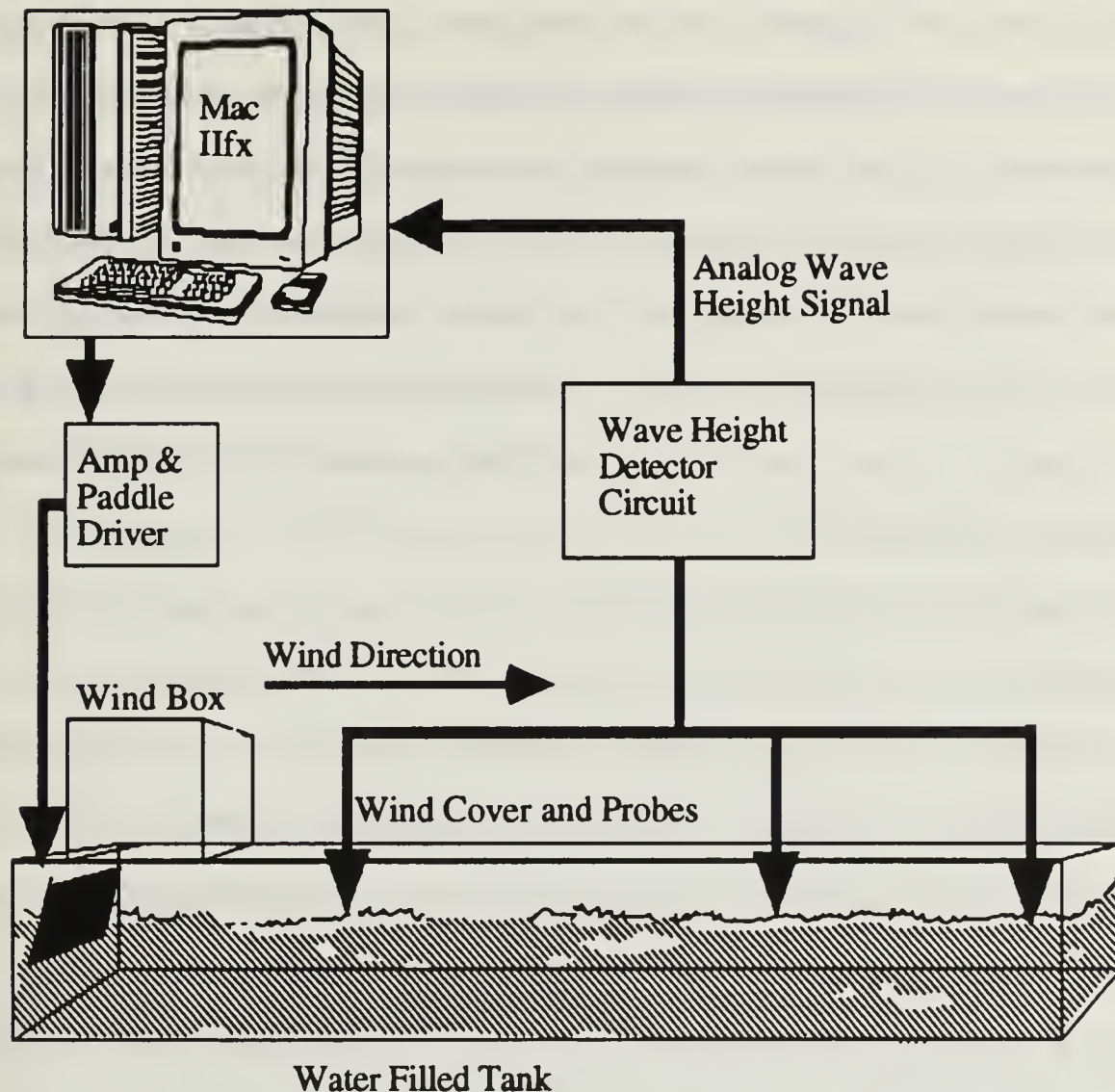


Figure 4.1 Overview of Experimental Setup

The computer, a Macintosh II fx running LabVIEW 2.2 (commercial software), is the hub of the experiment. LabVIEW is an icon driven, object oriented, high level computer language. Its intent is to enable the computer to function as a programmable electronic instrument. A “program” thus has a front panel and a wiring diagram. These programs are referred to as “virtual instruments.” The front (or control) panel has switches and controls which allow modification of program parameters while the program is running. In the wiring diagram mathematical and other miscellaneous operations on data are depicted with

icons that are “wired” together to provide data paths. Via this program, the computer can be made to control the input burst of waves as well as data collection and analysis.

The wind in the tank serves to generate a background spectrum of waves, which can be varied depending on the number of fans used. The more fans used, the higher the wind velocity and the lower the spectral peak frequency. Additionally, the spectral peak is a function of position along the tank, as fetch is required to achieve the lowest steady spectral peak frequency. Closer to the wind box the typical wavelengths are short, and lengthen farther down the tank.

The wave height detector probe can be positioned at various places along the tank (where the wind cover can be removed to allow access). In this experiment a run consists of hundreds of individual launched pulses and data manipulation for a particular burst, fan, or detector location. The sequence of events that comprise a “complete run” starts with the launching of a pulse, immediately after which the data acquisition board begins sampling the analog output from the wave height detector for a specified time. After the time series is completely sampled, it is manipulated to give a specified type of output and averaged with any previous data from the run. Finally, a random waiting period occurs before the next pulse launch to prevent any possible coherent addition of events from one launched pulse to another. The process is repeated many times, and the data averaged to increase the signal to noise ratio. In this manner, the coherent response of the system of waves can be found among the random wind driven waves.

## **B. COMPUTER CONTROLLED PADDLE**

The paddle can be driven by coherent or noise burst waveforms via a Burst Generator Virtual Instrument called by the controlling LabVIEW program. In the case of coherent bursts, the frequency, amplitude, and duration of pulse can be chosen. Noise bursts can be controlled similarly, but instead of definite frequencies, the cutoff frequencies of a

bandpass filter can be chosen. A variety of time domain windows can be applied to the raw burst data in order to smooth the reaction of the paddle at leading and trailing edges of the burst. All of these controls can be seen in the front panel of the burst generator instrument shown in Figure 4.2 and its implementation shown in Fig 4.3. The output amplitude of the signal is measured in volts directly on the virtual instrument. The analog output voltage used to drive the paddle is generated by a 16 bit digital to analog converter on a National Instruments NB-MIO16X data acquisition board.

In the controlling LabVIEW program, either a new or a different burst can be chosen for each launched pulse in the run. This is useful in the case of noise pulses, in order to remove any results that may be attributable to a particular waveform. This program also specifies what form the output data will take, how many averages are to be made, and allows control over wait times between the end of wave height data collection of one particular burst to the launch of the next burst.

### **C. COMPUTER CONTROLLED DATA COLLECTION**

Immediately following each launch of a wave pulse, wave height data is sampled as follows. The analog output signal from the wave height detector is converted to a 16 bit digital signal and sampled at a specified frequency (normally 50 or 100 Hz) by the NB-MIO16X board. The number of samples as well as sampling frequency can be controlled on the front panel of the Data Acquisition Virtual Instrument. Once the time series is taken, a choice must be made as to what form the final output will take. The selection of the averaged output is made from the Waveturb Virtual Instrument itself from the following: wave height, RMS wave height, and Moving Fast Fourier Transform (FFT). An average of wave heights is simply that. The time series taken following each burst is averaged the number of times specified for the run. The RMS wave height output is calculated by taking the square root of the average of the square of the data with its mean subtracted. The





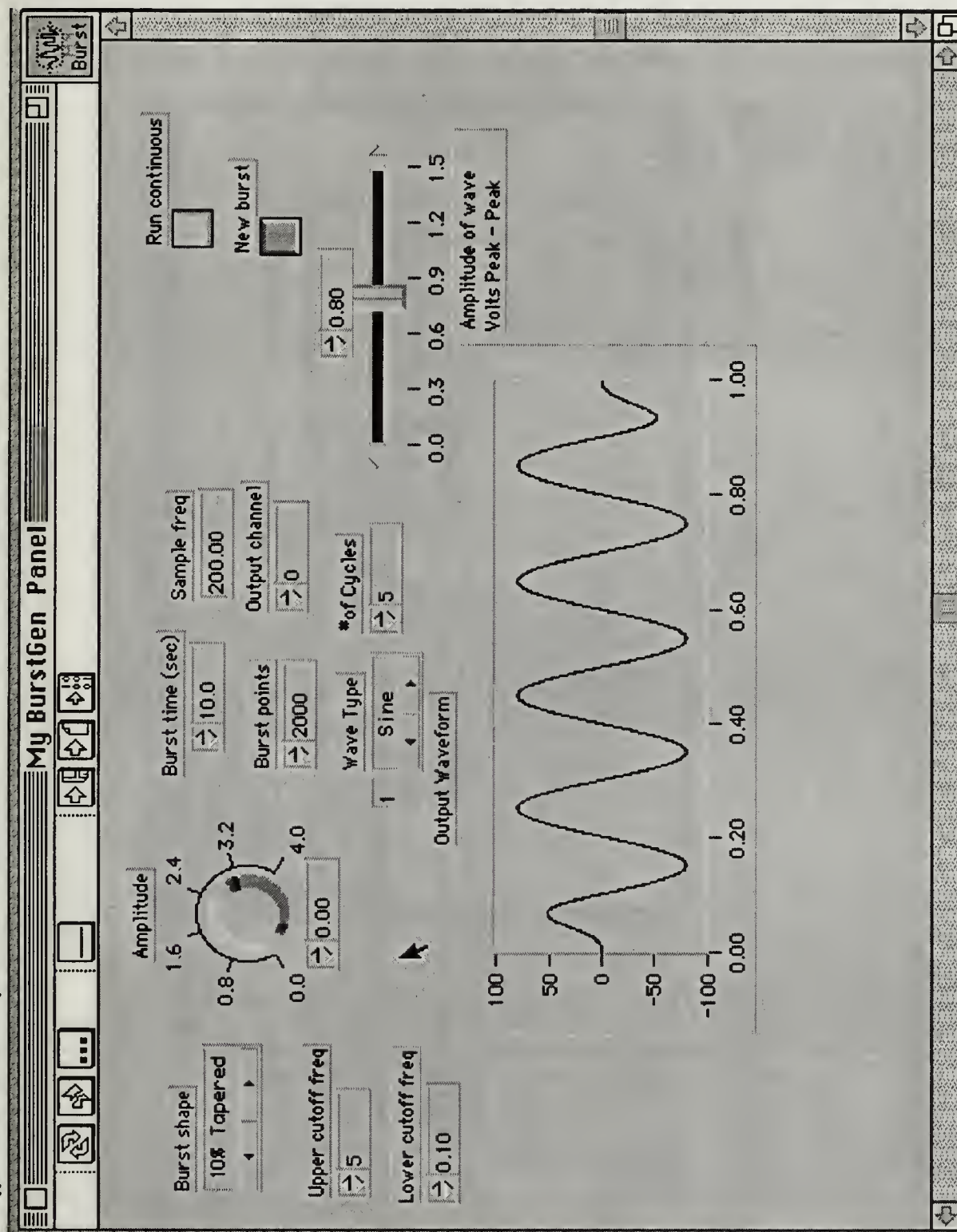


Figure 4.2 Burst Generator Front Panel (LabVIEW)



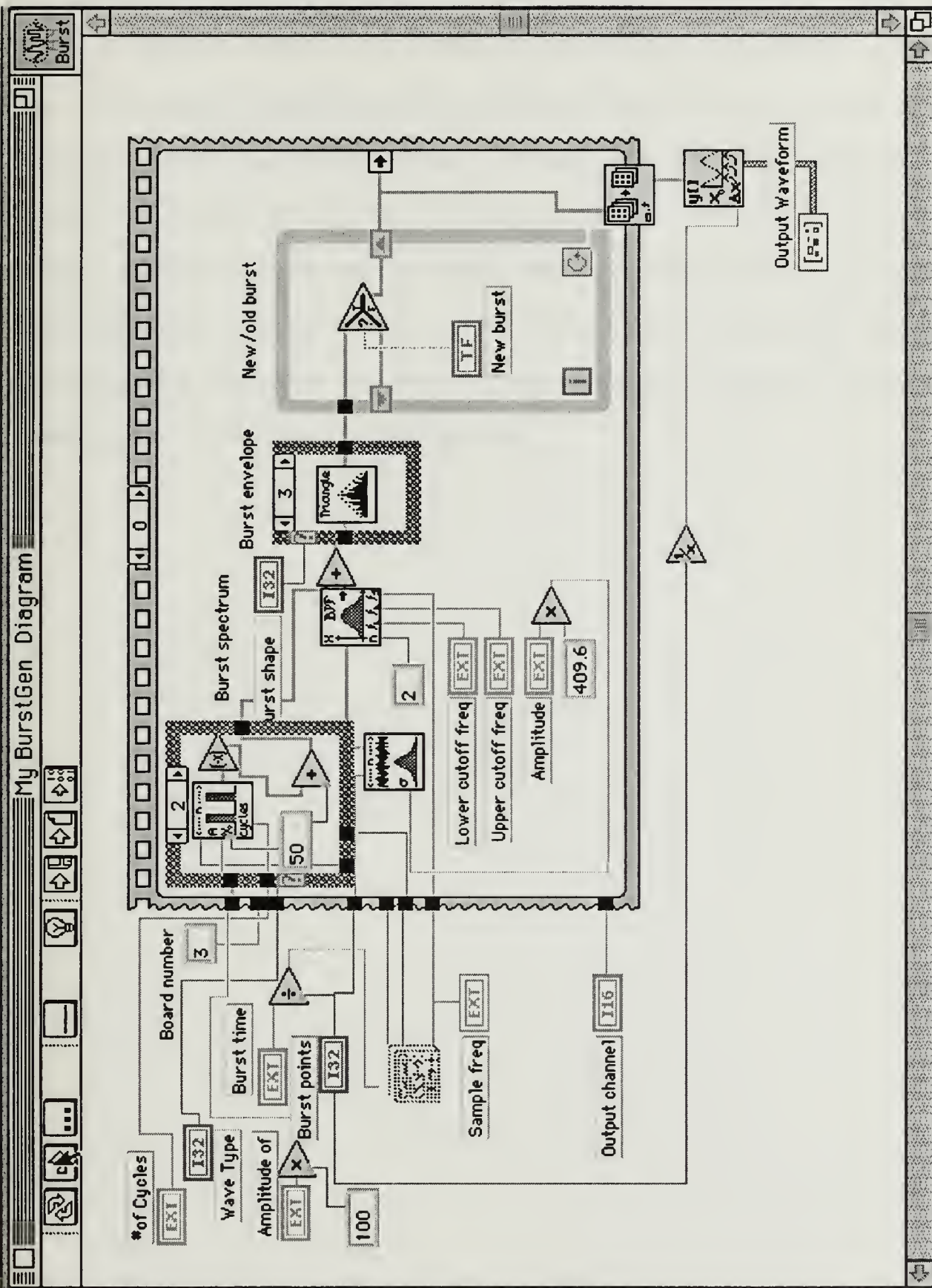


Figure 4.3 Burst Generator Wiring Diagram (LabVIEW)



Moving FFT output yields essentially a spectrogram with an output matrix of values proportional to the spectral density as a function of time. This matrix is calculated by breaking up each time series into a smaller time sample with an optimum length of 100 points. A Hamming window is applied to this smaller sample, and its power spectrum calculated by a built in LabVIEW routine. The small samples are overlapped by 50% to smooth the output in time. The spectral density versus time for each launched pulse is averaged. Regardless of the type of output chosen, and after the run is complete, the averaged data can be automatically saved to an ASCII formatted file named by the operator. The Moving FFT subroutine will place the data in a format accepted by the Spyglass graphing package conducive to 3-D surface plots.



## V. RESULTS AND INTERPRETATION

### A. WAVES AND TIME OF FLIGHT

The most usable form of displayed data is a greyscale or color image with the scale proportional to the spectral density. Often contour lines are used in combination with the greyscale or color presentation and are helpful in determining particular characteristics of the image. A simple narrowband burst of known frequency will show a localized area of increased energy with a time of flight given by the dispersion relations shown in Section II.B. An example is shown in Figure 5.1. For a wideband burst (noise), the displayed image will show a straight line of increased energy again determined by the time of flight for all frequency components of the burst. The apparent horizontal streakiness of data in Figure 5.1 is caused by a low number of averages (ten) and also due to the absence of time domain windowing for the time series subsections. Using nominal values for the acceleration due to gravity, and a paddle to wave height probe distance of 4.1 meters, the time of flight  $T$  in seconds as a function of frequency in Hertz from paddle to probe is given by:

$$T = 5.25 f.$$

As can be seen, the plotted data are consistent with the above result. A straight line can be drawn from the origin along the maximum energy density peaks as indicated by the peaking contours with a slope of approximately  $1/5.25$ . When the detector is placed at the end of the wind tunnel, the paddle to probe distance is 17 meters and the constant of proportionality between frequency and time of flight is 21.8 as in Figure 5.1.

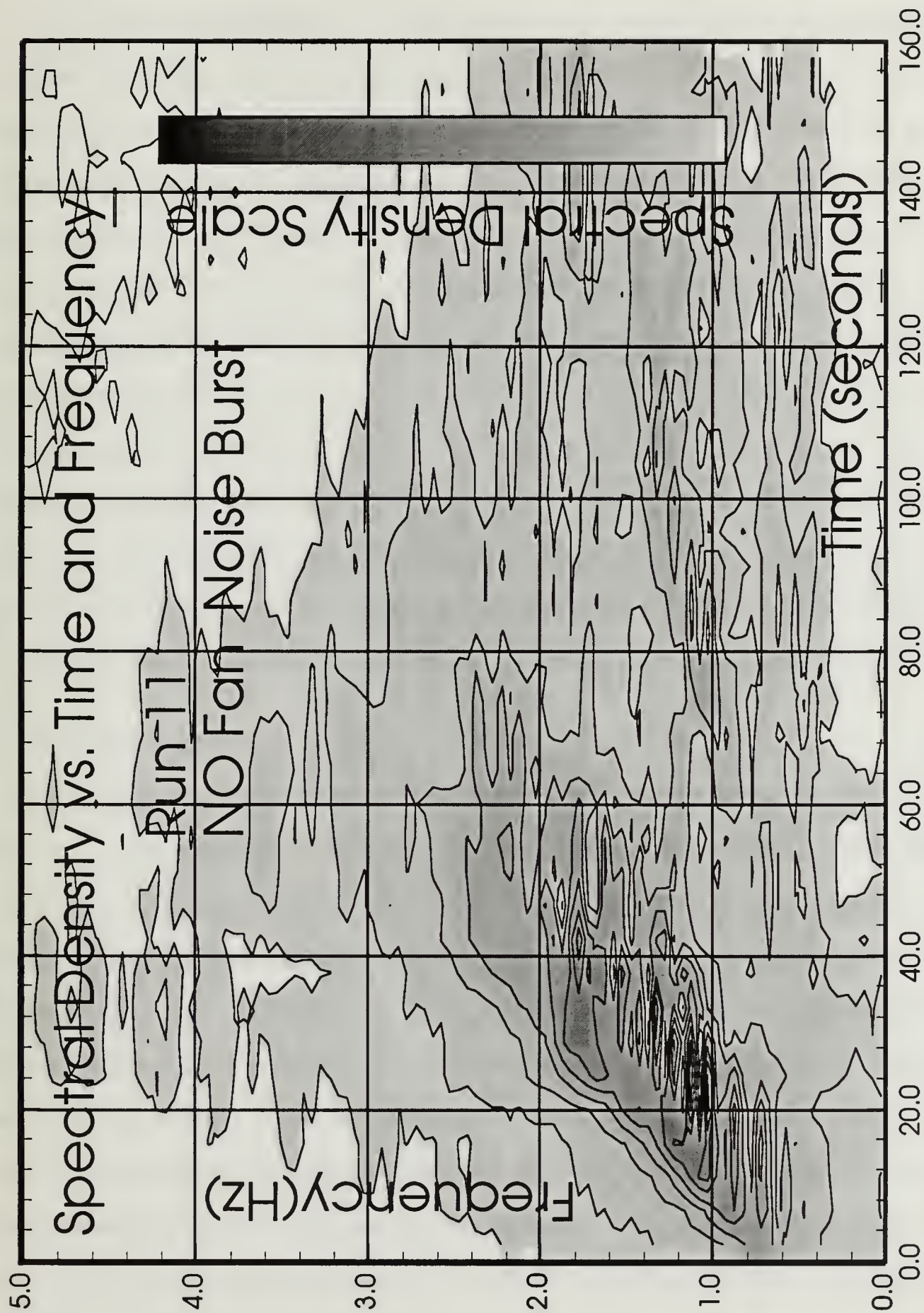


Figure 5.1 Example of Linear Time of Flight as Function of Frequency for Wideband Burst



Other observations typical of the paddle and tank responses can be made from Figure 5.1. First, energy due to reflection from the far wall can be seen at frequencies just above one Hertz occurring at a time of approximately 40 seconds. Secondly, it can easily be seen that although the paddle was driven with an input signal with cutoff frequencies of 0.1 and 5.0 Hertz, the resulting propagating waves show very little energy above 2.0 Hertz. Lastly, an effect on narrowband wave bursts, which is not shown in the image, is an apparent, occasional frequency shift. For example, it was observed at one point that an input frequency of 3.0 Hertz yielded a spectral energy peak at 2.5 Hertz. This last effect was not deeply investigated, but may be a combination of paddle reaction, and effective filtering of the waves because at higher frequencies, transverse rather than longitudinally propagating waves are produced. Also, transverse waves are parametrically excited in the volume of water between paddle and wall possibly at frequencies that are subharmonics of the paddle drive. The energy stored in these waves leaks out for several seconds after the excitation has stopped, and may be a mechanism for the apparent downshift in frequency.

## **B. WIND SPECTRA**

The particular spectra of different fan combinations is presented extensively by Yarber (1992). Of greatest interest in this experiment is the spectral peak created by a particular combination of fans at a nominal water height. Unfortunately, only approximate wind speeds could be obtained because an appropriate measuring device was not available. It was found that at 4.11 meters from the paddle end of the tank that the winds were highly variable (turbulent), and thus were difficult to measure. At this position, using fan number two, wind speeds varied in time from 1.5 to 5.0 meters per second in one side of the tank, while the other side was more steady at approximately 3.3 meters per second. The wind speed at centerline was 5.7 meters per second. At the end of the wind tunnel, wind speeds were more steady, but unfortunately near the threshold of the measuring instrument, a hand



held "Turbo-Meter" wind speed indicator. For fan number two, the measured speeds to within .1 meter per second are given in Table 1. Readings were taken along a horizontal midway between mean water height and the top of the wind tunnel.

**TABLE 1. MEASURED WIND SPEEDS FOR FAN NUMBER TWO AT END OF WIND TUNNEL**

<b>Distance From CL in cm</b>	50	40	30	20	10	0
<b>Measured Wind Speed in m/sec</b>	<.1	.4	.4	.6	.6	.5
<b>Distance From CL in cm</b>	-10	-20	-30	-40	-50	
<b>Measured Wind Speed in m/sec</b>	.7	.7	.7	.8	.3	

The spectral peaks of wind generated waves for different fan combinations were found using an HP 3562 Dynamic Signal Analyzer averaging 50 one minute samples without overlap. The measured values found at the end of the wind tunnel are given in Table 2.

**TABLE 2. MEASURED SPECTRAL PEAKS FOR ALL FAN COMBINATIONS AT END OF WIND TUNNEL**

<b>Fan Numbers</b>	1	2	3	1 & 2	1 & 3	2 & 3	1 & 2 & 3
<b>Peak Frequency (Hz)</b>	4.3	2.6	2.6	2.3	2.3	2.2	2.1



As expected, the steady state spectral peak decreases with increasing wind speed. The above results are somewhat redundant when using the spectrogram images which contain unperturbed wind information for a period of time preceding the arrival of the burst, but they are helpful in planning burst-fan combinations for experiment runs. Figure 5.2 shows spectral density data for fan number three alone taken at the end of the wind tunnel (17 meters from the paddle end of the tank). The image shows clearly that over the averages taken, the spectrum is constant near a particular frequency as indicated by the horizontal line of highest energy density, in this case just less than 3.2 Hertz. Additionally, the bandwidth does not change appreciably with time, since the shades indicating relative spectral density are constant along a horizontal.

### **C. WIND AND WAVES: A COLLECTIVE MODE**

This experiment culminates in the interaction of a launched burst with a background of random waves. A plot of RMS wave height shown in Figure 5.3 taken directly from the Labview output clearly shows a decrease in wave height at a time of approximately 50 seconds, the period of higher wave energy preceding it is due to the input burst energy. The distinction between input burst energy and the effect due to the suspected collective mode can be made by examining spectral density versus time and frequency plots. As shown in Figure 5.4 there is a reduction in the energy of the background wind driven waves that occurs at all frequencies at the same time, between 40 and 50 seconds. This is suspected to be the collective mode. The input burst in this case is identical to that of Figure 5.1: a two second “ten percent tapered” noise burst with cutoff frequencies of 0.1 and 5.0 Hertz. A more dramatic effect can be seen in Figures 5.5, 5.6, and 5.7. Figure 5.5 shows the effect of the two second three Hertz “ten percent tapered” burst alone. It is similar to the one displayed on the output of the “Burst Generator:” virtual instrument in Figure 4.1. Figure 5.2 shows the wind generated spectra alone. In Figures 5.6 and 5.7,



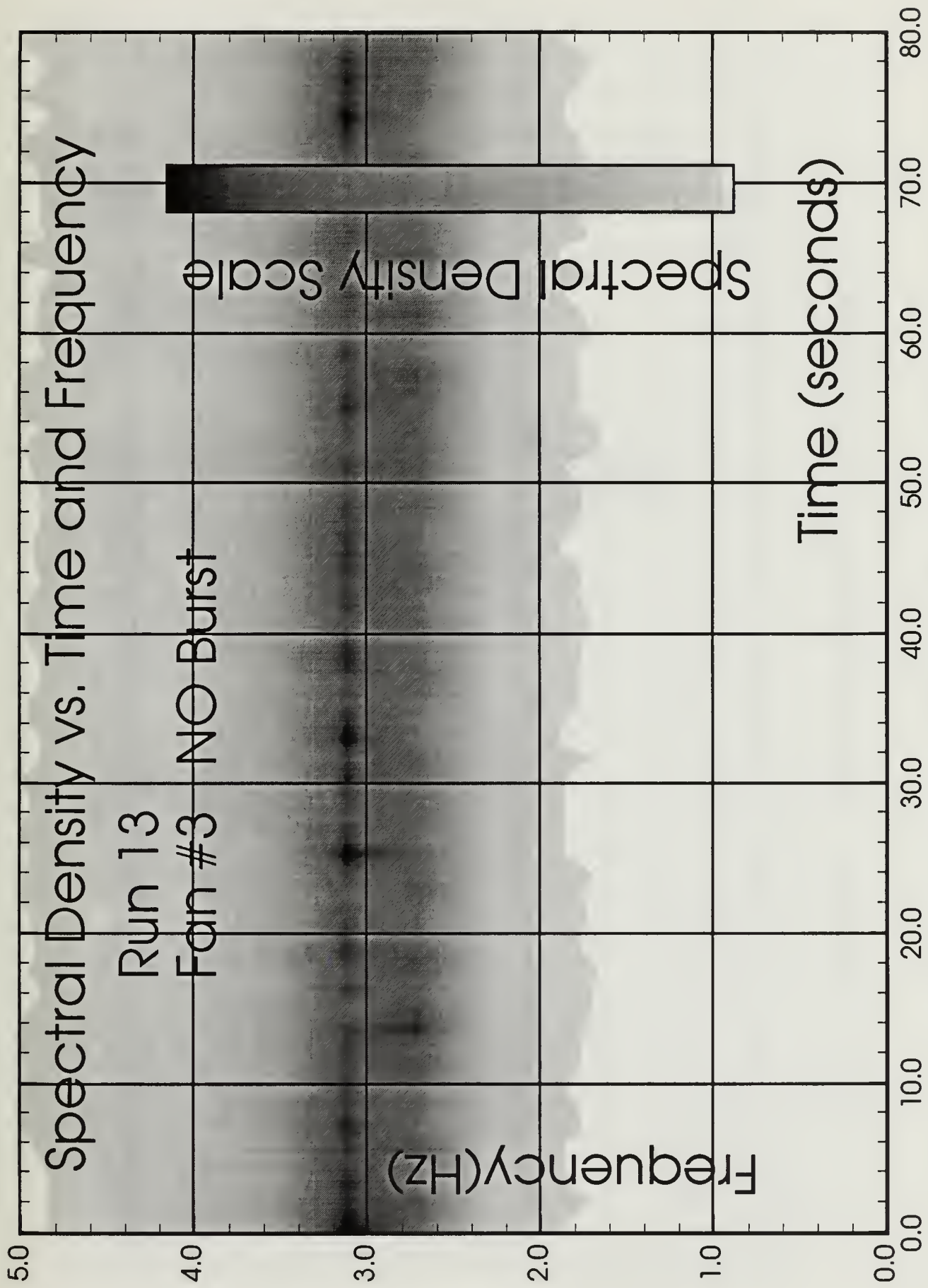


Figure 5.2 Representation of Spectral Data Due to Wind Waves Only



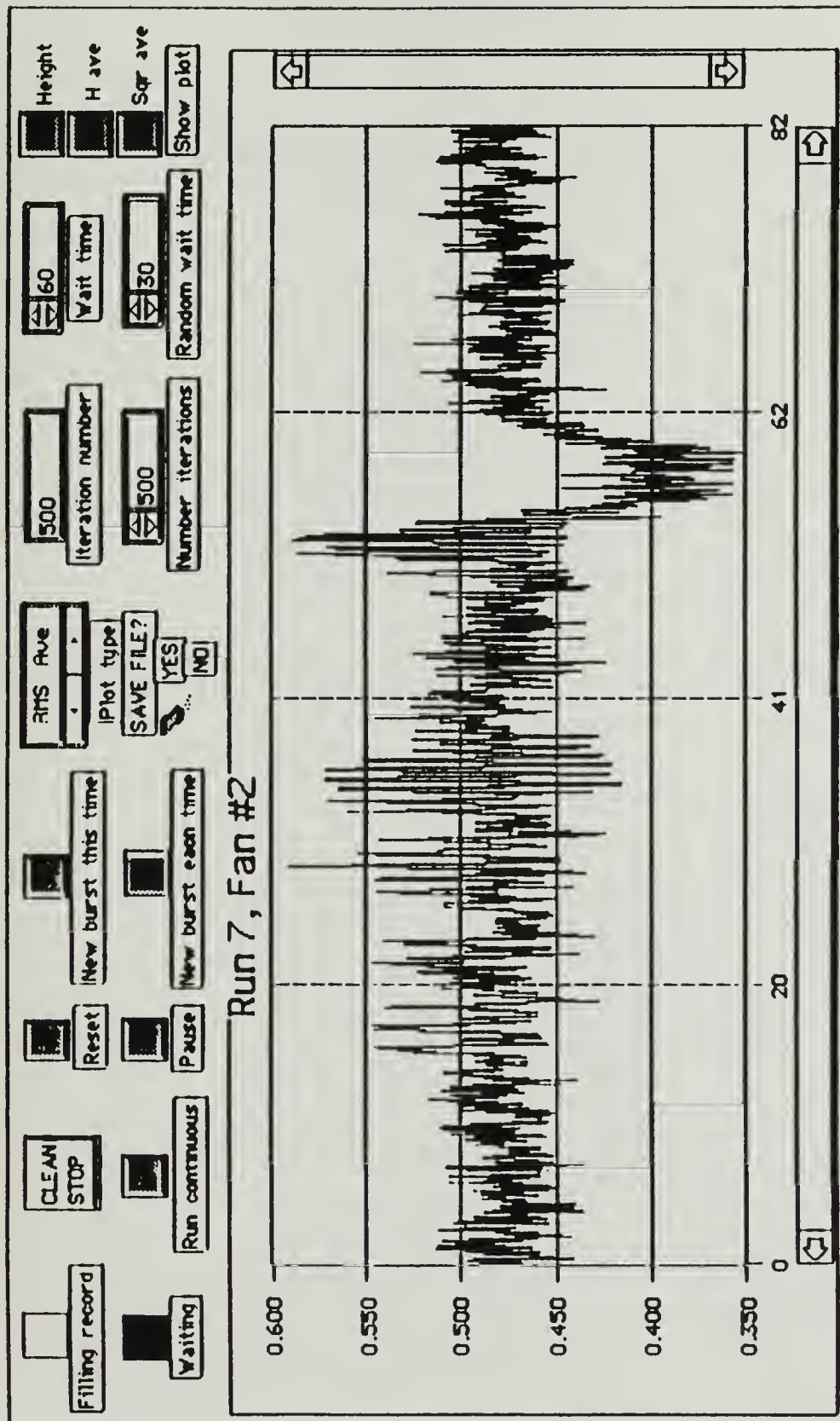


Figure 5.3 RMS Response of Wind-Wave System to Input Burst (Labview)





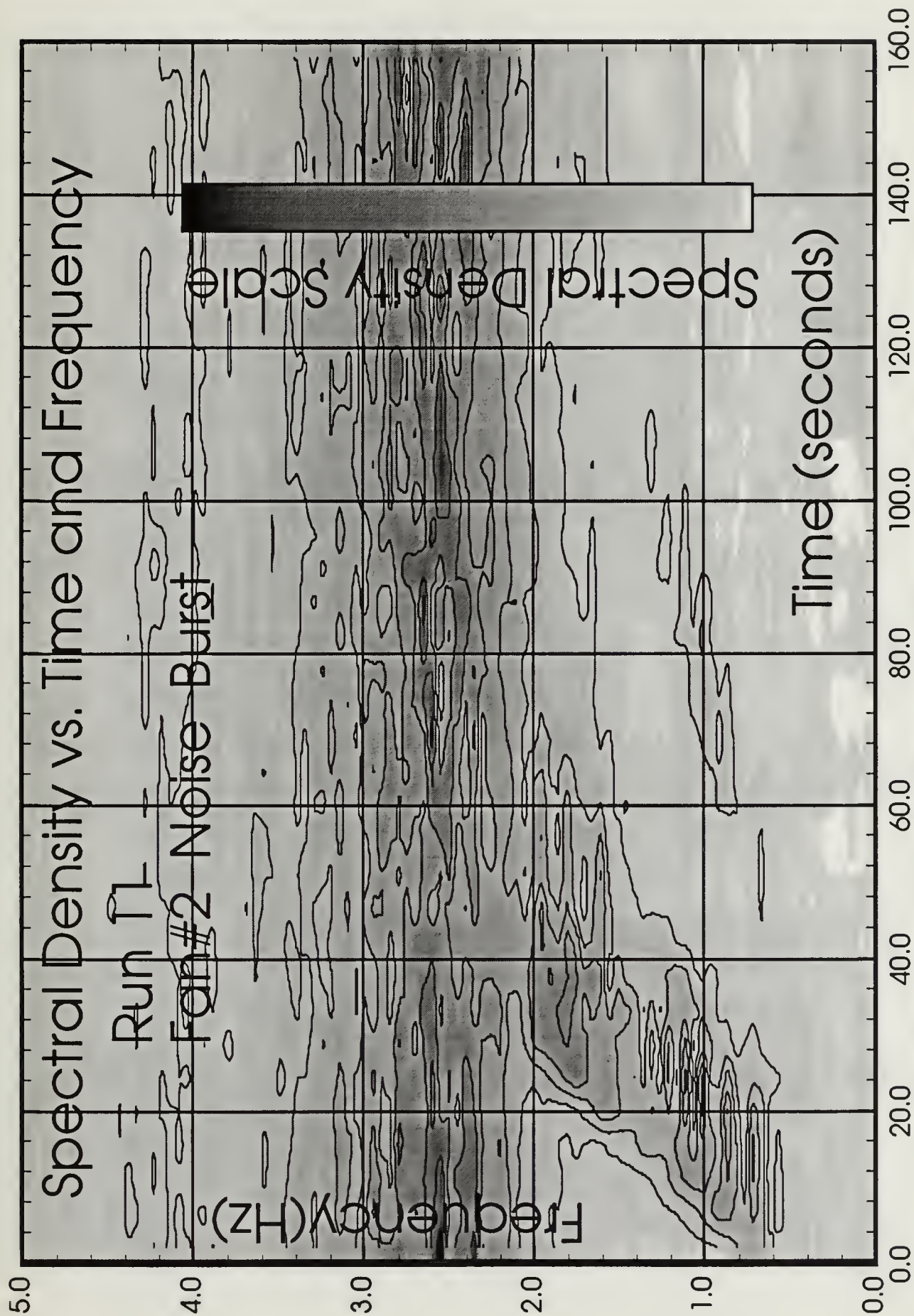


Figure 5.4 Response of Input Burst from Fig 5.1 with Wind Applied



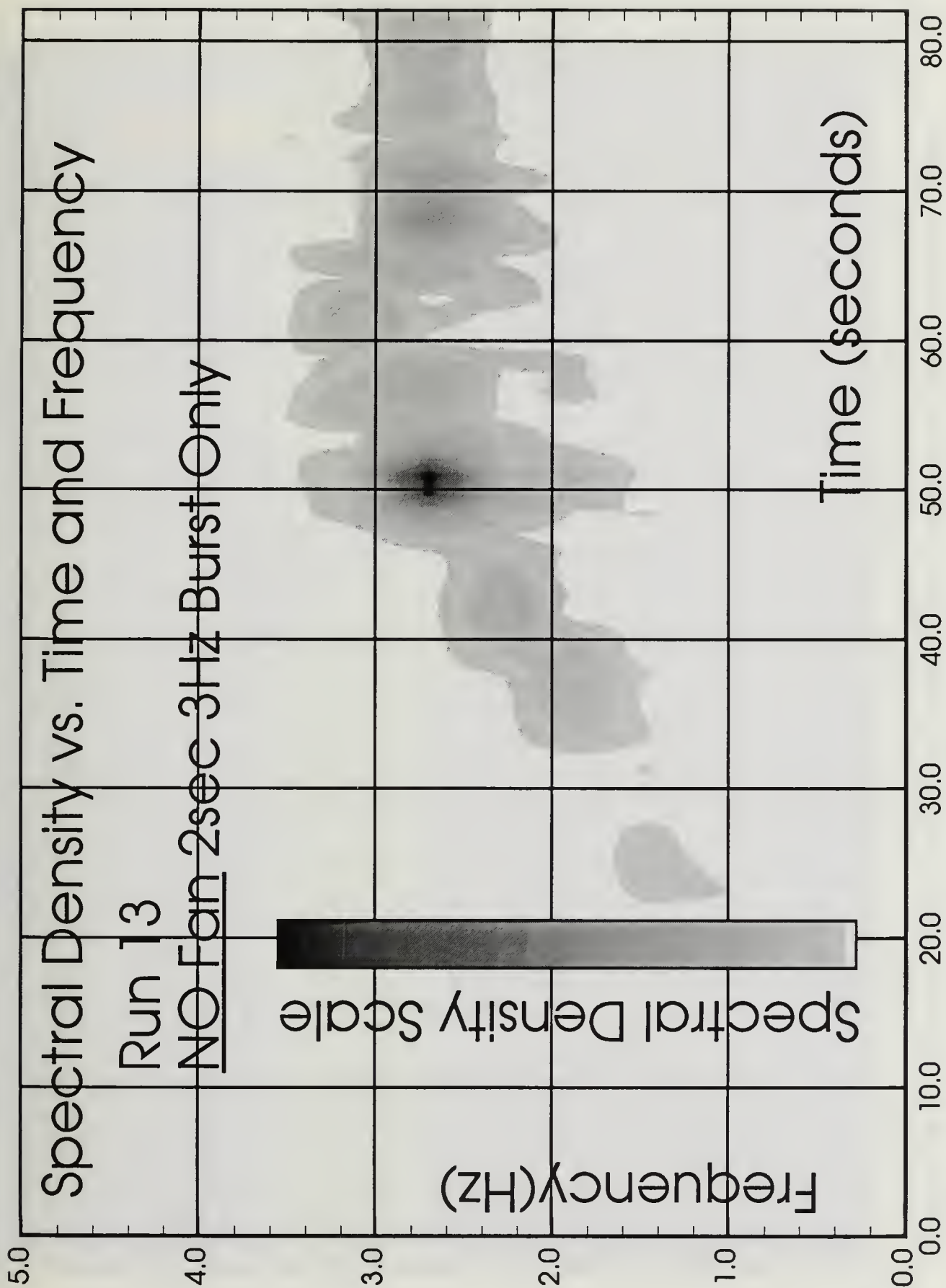


Figure 5.5 Narrowband Burst of Waves Without Wind Generated Background Waves





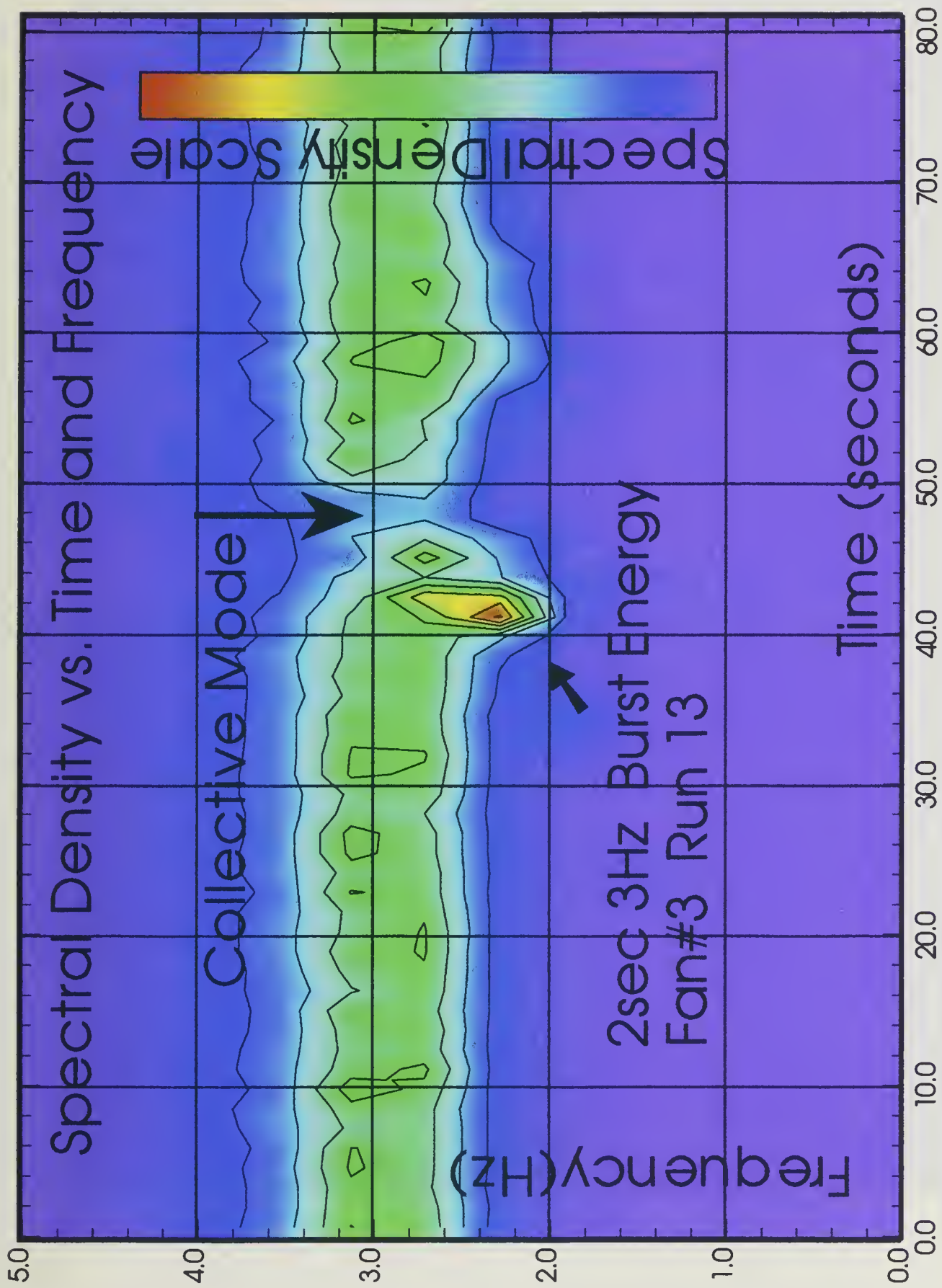


Figure 5.6 Effect of Burst on Background Wind Spectra Showing Possible Collective Mode



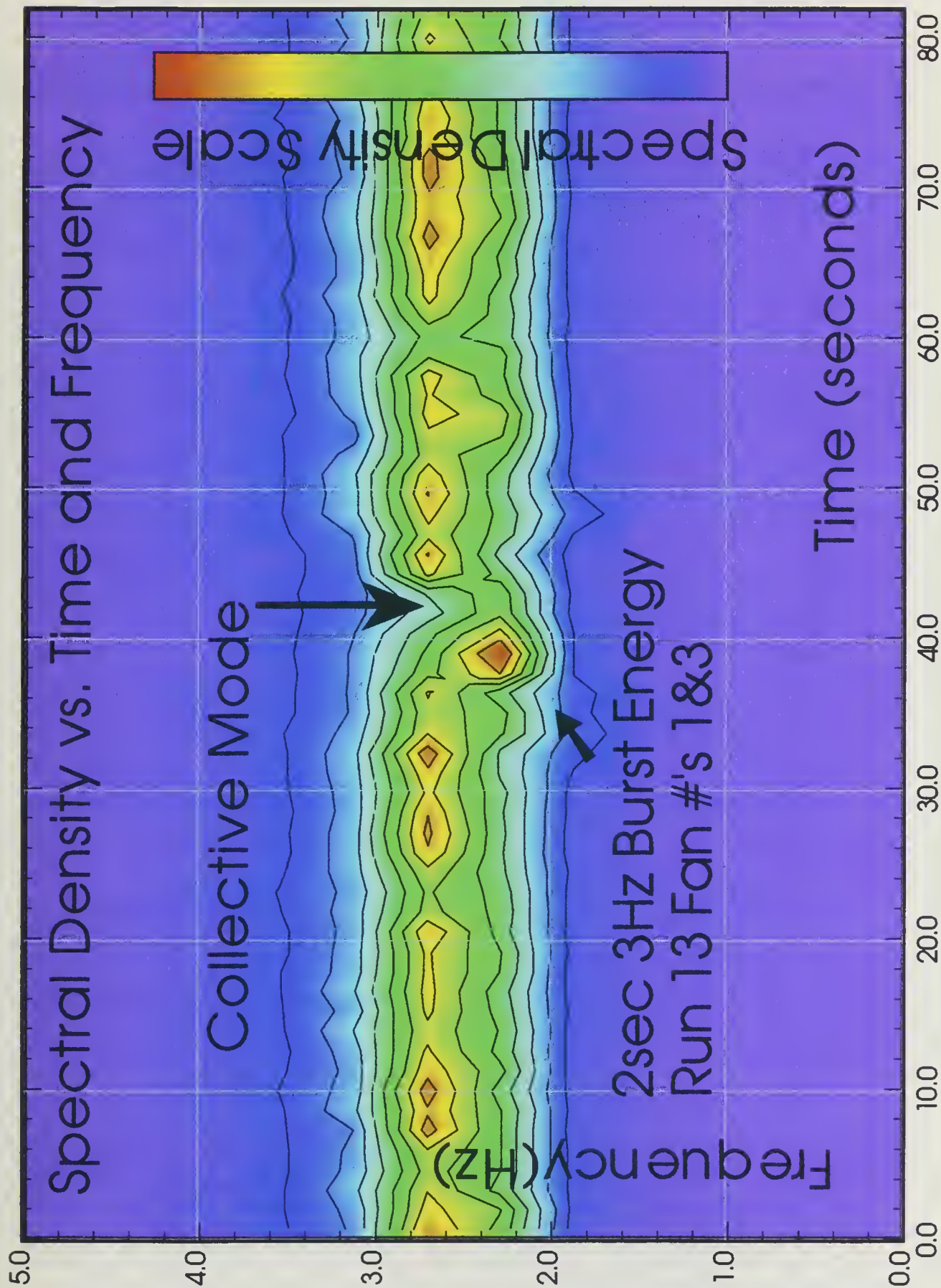


Figure 5.7 Different Background Spectra Affected by Burst as Shown in Figure 5.5





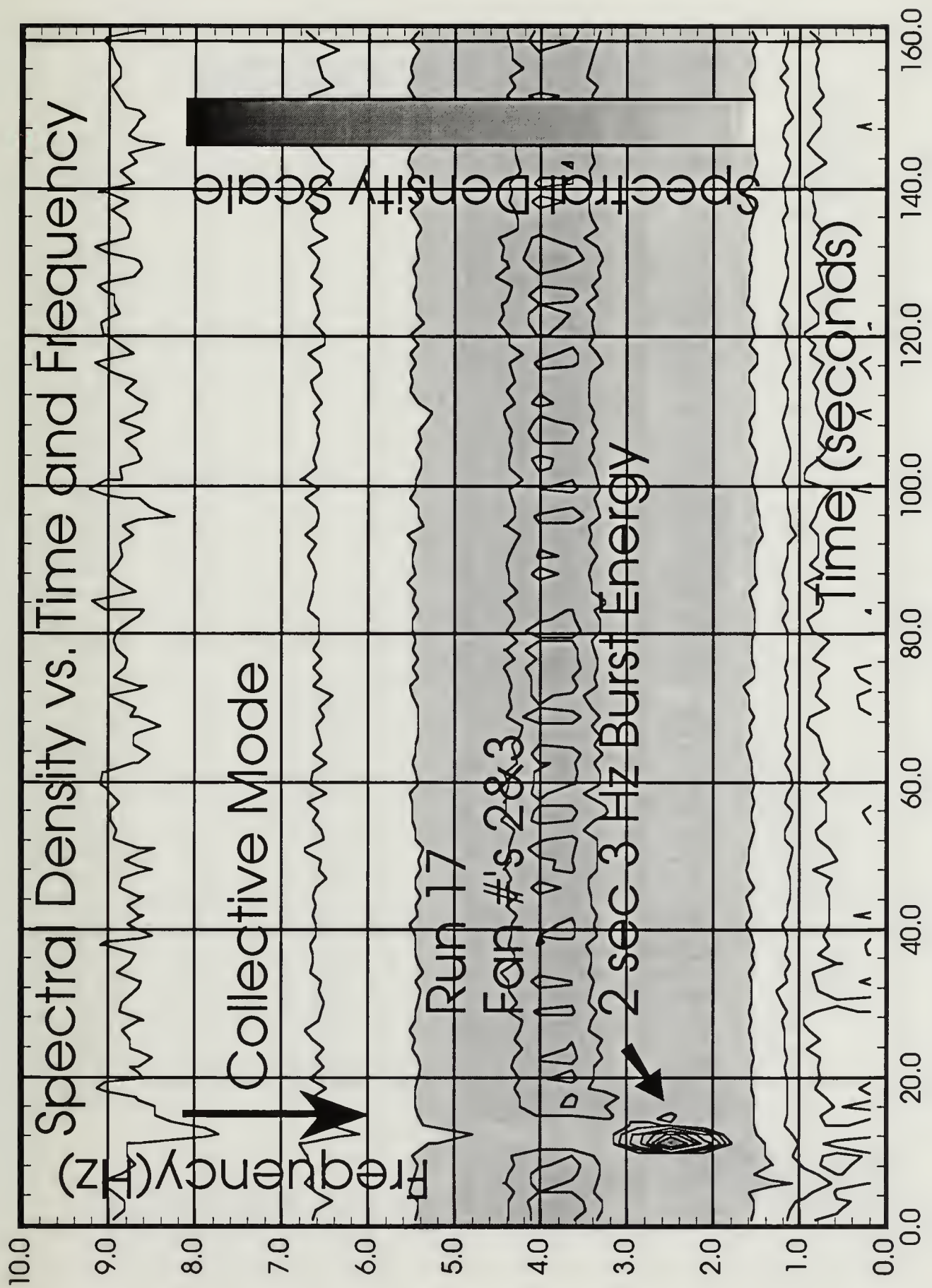


Figure 5.8 Response of Coherent Burst Close to Paddle









the collective mode can be seen as a decrease in the background spectral density at 48 and 43 seconds, respectively, following the burst energy for two different combinations of fans. Figure 5.8 with its expanded axes shows the response to the same burst when the probe is 4.1 meters from the paddle. Figure 5.9 is the response 4.1 meters from the paddle of a noise burst. In this series of images (Figures 5.5 through 5.9) of bursts in combination with wind, the reduction in spectral density is vertical: that is occurring at one moment in time. On contour plots, it appears as a “valley” running straight up, perpendicular to the horizontal wind energy. In shaded plots, it appears as lighter or more blue shading in a vertical direction. It must be emphasized that in all of the figures shown with bursts launched into a background of wind driven waves, the reduction in background energy of the wind generated waves occurs at all frequencies simultaneously: it is nondispersive. This is a distinguishing characteristic of the collective mode, and is clearly present in the data above. A second important property of the collective mode, is that it propagates at a speed proportional to the random background spectra: that is, independent of the burst. Comparison of Figures 5.6 and 5.7 (where the probe is 17 meters from the paddle) with Figures 5.8 and 5.9 (where the probe is 4.1 meters from the paddle) reveals that the separation time between pulse and collective mode is greater for the longer separation distance. This strongly suggests that it is indeed propagating independently. Figure 5.10 summarizes all available data by plotting speed of the “notch” or collective mode as a function of background spectral peak group velocity. Since the data is taken from plots similar to those shown, interpretation of arrival time is highly subjective, thus the large error bars surrounding each point. From a best fit line, the slope is approximately 0.55. This supports the notion that the mode propagates at a speed proportional to the group velocity of the background spectra.

Another observation can be made from Figures 5.11 and 5.12. That is that the input burst energy does not propagate at frequencies above the background spectral peak. The

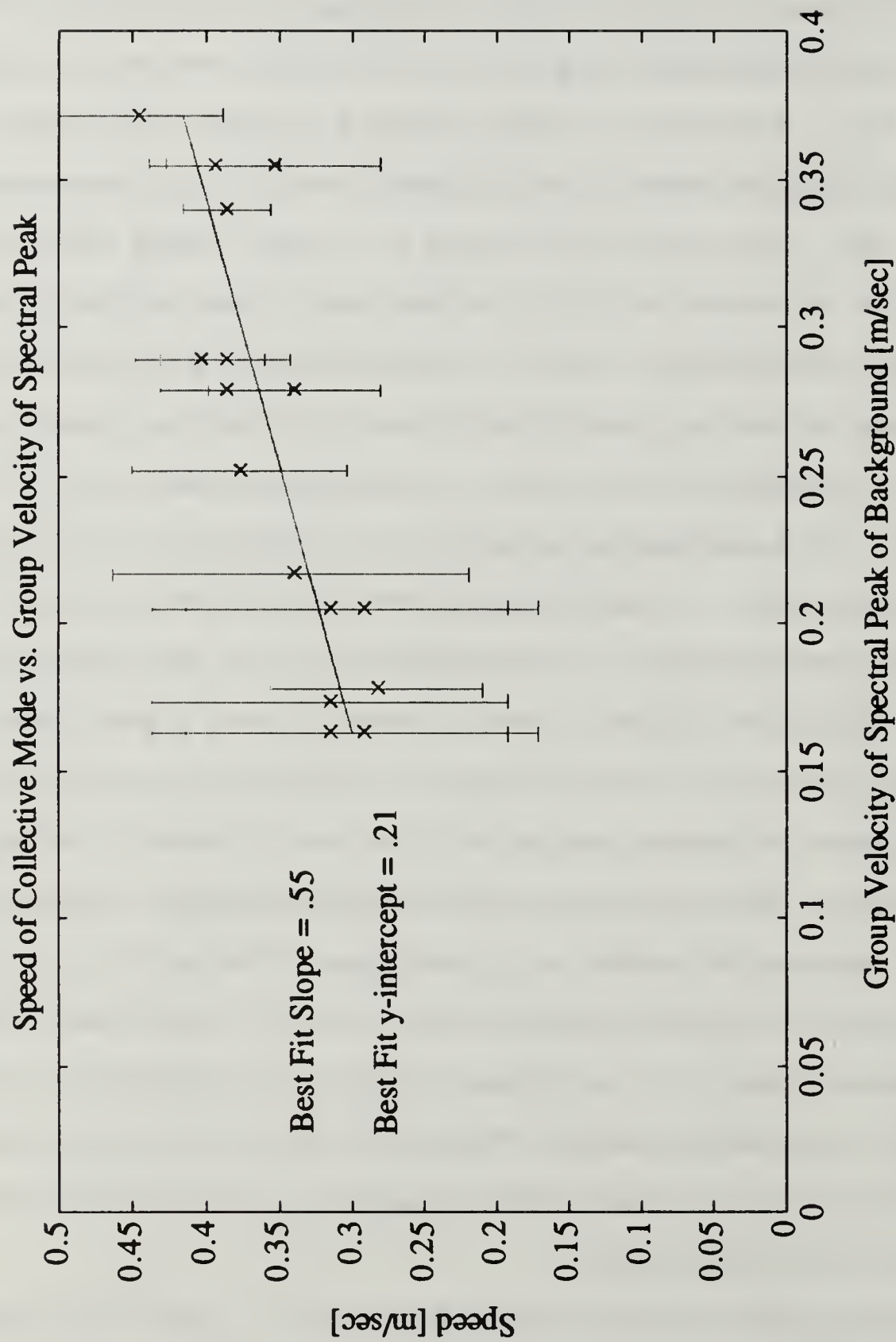


Figure 5.10 Summary of Collective Mode Propagation Speed vs. Group Velocity of Spectral Peak



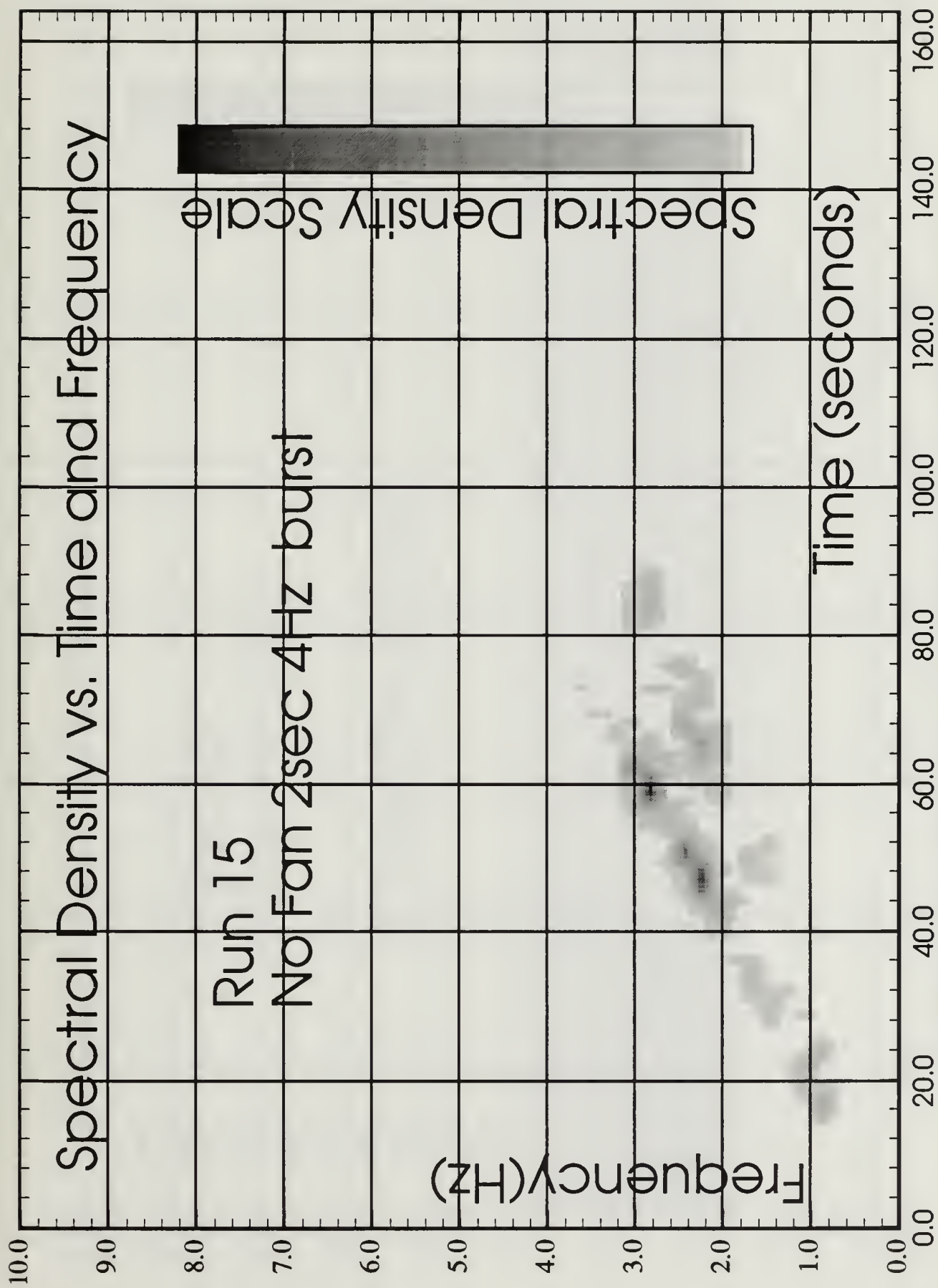


Figure 5.11 Different Burst With Energy at High Frequencies



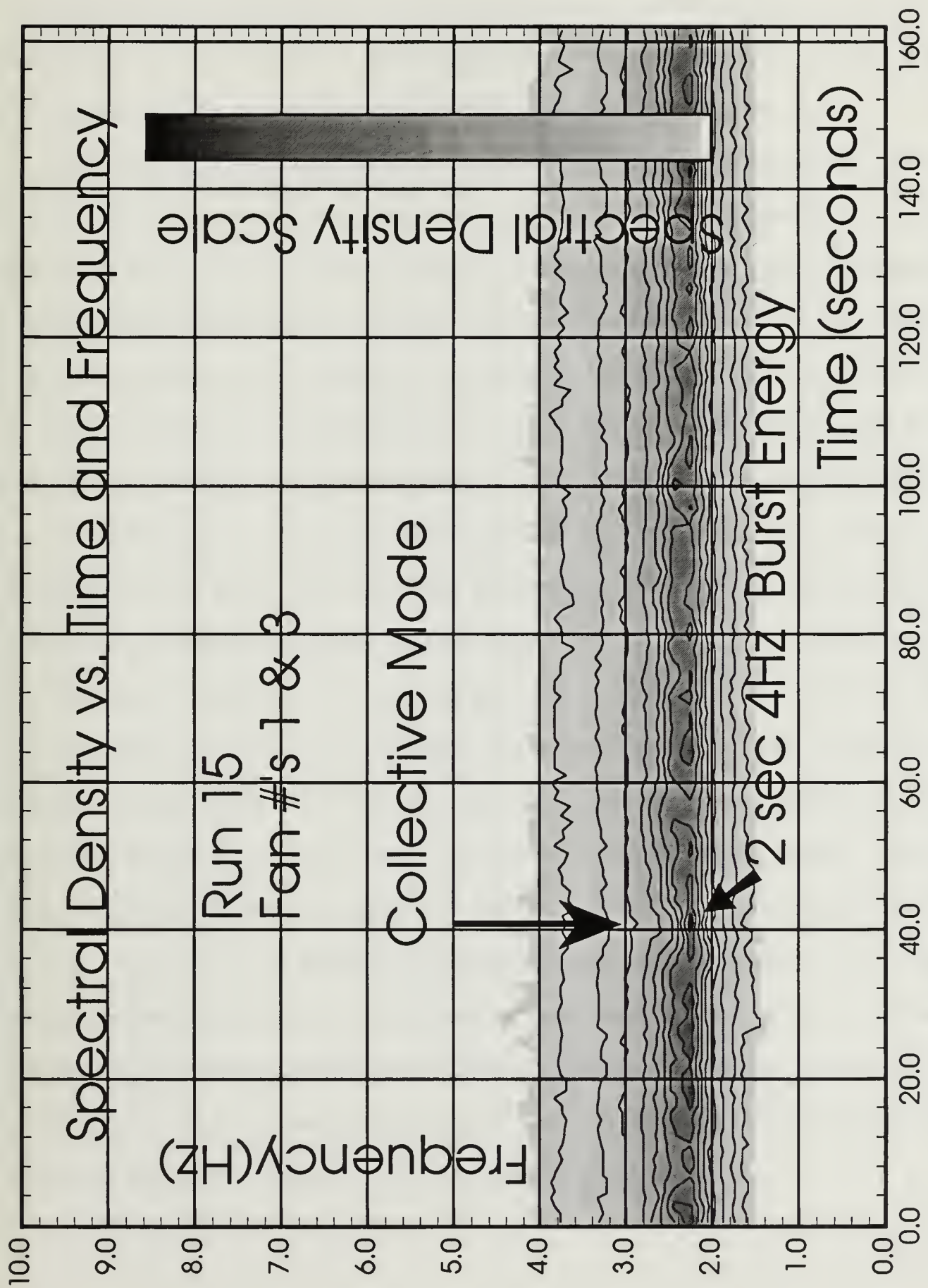


Figure 5.12 Input Burst Energy Above Wind Spectral Peak Does Not Appear



input burst as shown in Figure 5.11 has significant energy at 3.0 Hertz. However, when wind is present (as in Figure 5.12) none can be detected. The nondispersive reduction in background waves can be seen at 40.0 seconds, but no high frequency components of the burst are present. The spectral density scale is the same in the two figures.

Figure 5.13 reveals several interesting artifacts of the burst and the wind-tank system. First, as can be seen in the burst, a relatively long (10 second) burst produces a spectral peak at 3.0 Hertz, whereas for shorter bursts (2.0 seconds, as seen in Figures 5.5 through 5.8) the spectral peak was as low as 2.3 Hertz as addressed in Section A of this Chapter. The burst also shows a low frequency component on its trailing edge. This might be a result of wave energy between the paddle and wall driving the paddle after the input burst ends. Also on this plot, two apparent spectral peaks are shown. The first near 4.8 Hertz is due to wind driven waves propagating away from the detector and probe. Since the detector is only 4.1 meters from the paddle, the fetch is small and thus the spectral peak is fairly high. The second, lower spectral peak at approximately 2.5 Hertz is probably due to fully developed wind driven waves propagating back toward the detector and probe following their reflection from the far wall. The reflection from the burst can be seen as increased spectral energy at 100 seconds and at about 2.1 Hertz. The mechanism for this apparent downshift is unclear, but can only be observed when wind is present. Another observation can be made by examination of Figures 5.14 and 5.15. These series show data taken 4.1 meters from the paddle for different fan and burst combinations. All of the images are normalized, that is the grey-scales are equal for each graph. Figure 5.14 shows that the energy of a noise burst does not increase in the presence of wind. However, if the burst is coherent as is the case in Figure 5.15, its energy is increased by either the presence of stronger winds or the background waves generated by the wind.





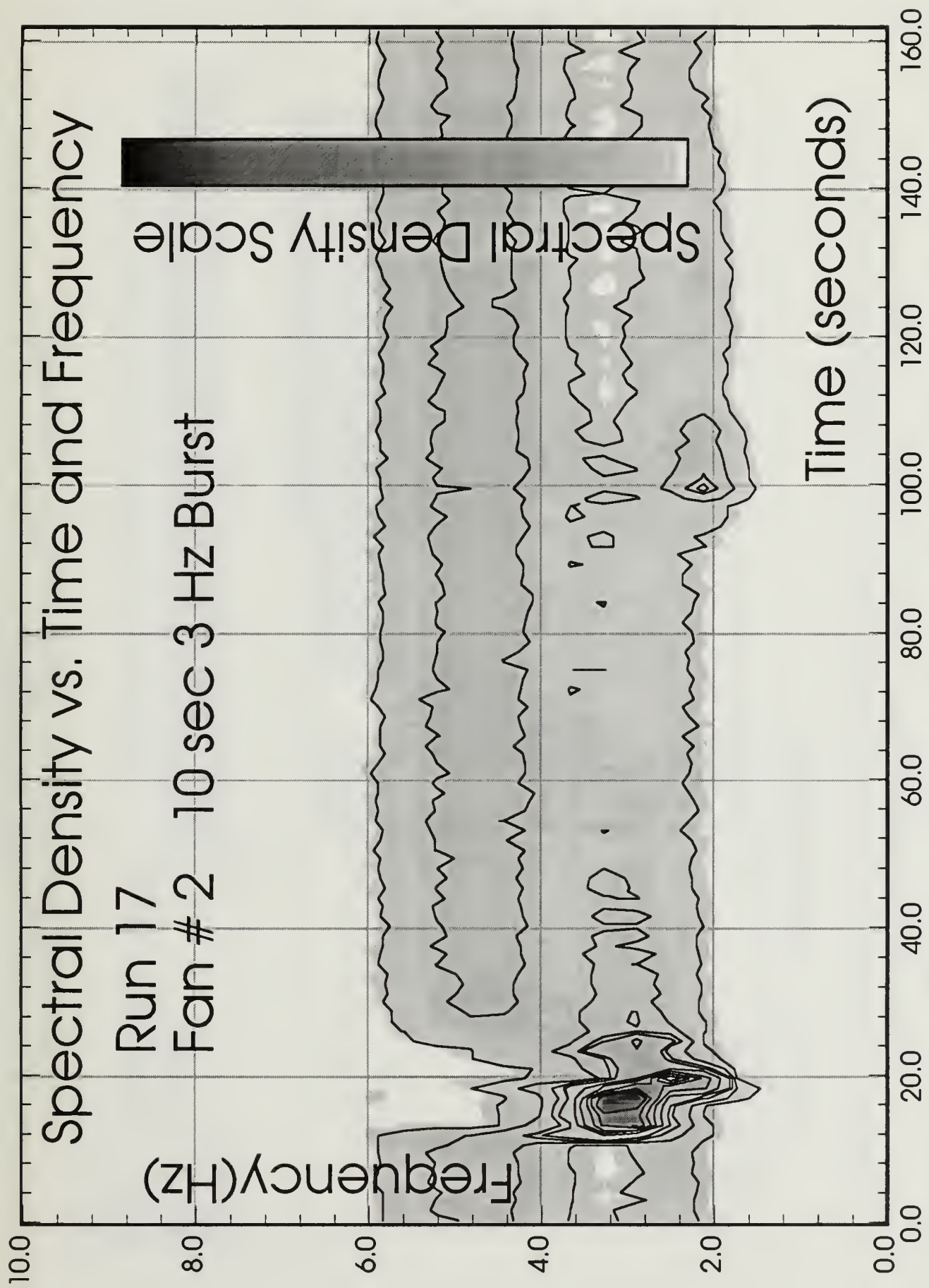


Figure 13 Unusual Response of Paddle for Extended Burst and Unexplained Downconversion



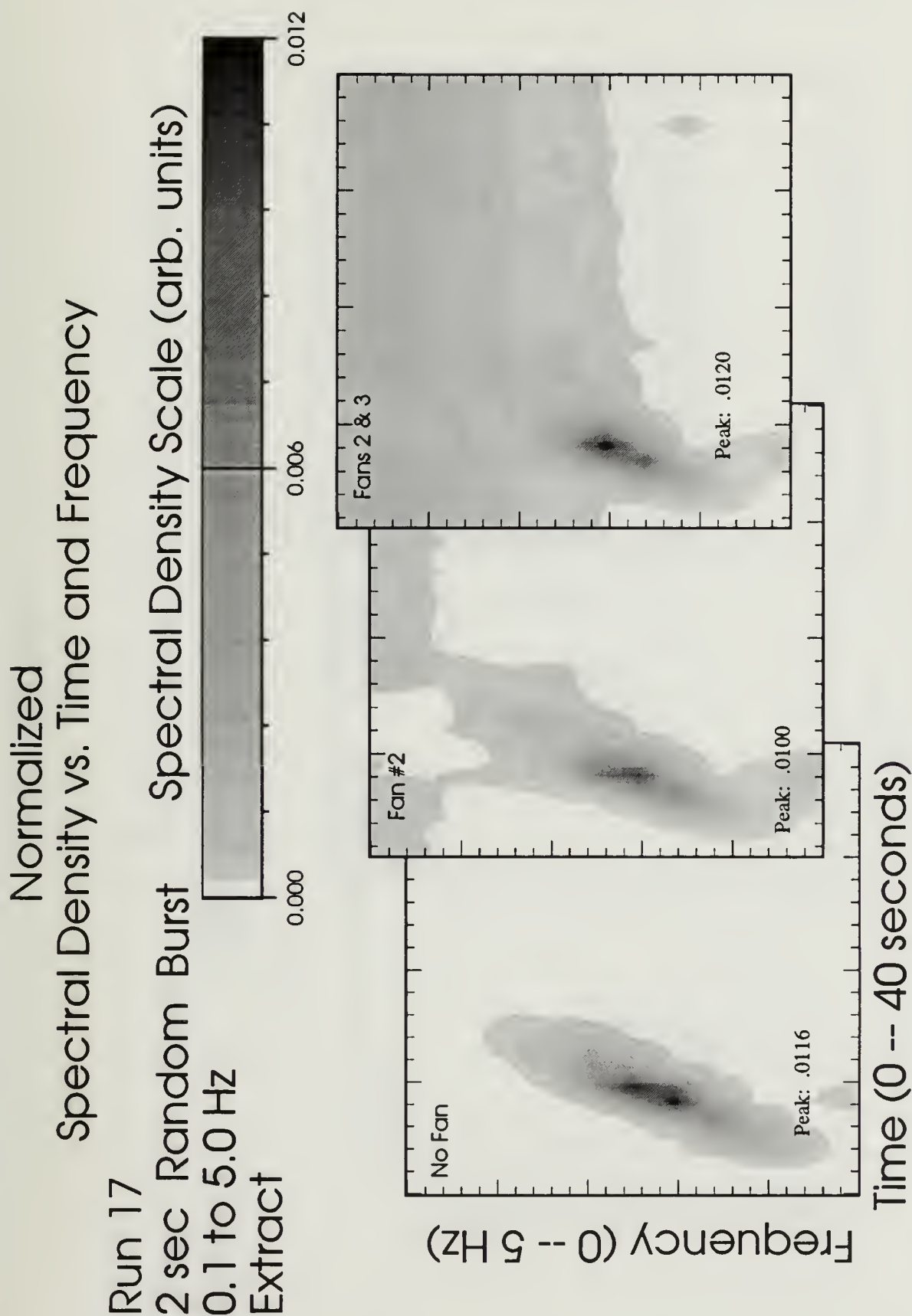


Figure 5.14 Relative Peak Spectral Density Does Not Increase as Function of Wind Speed for Wideband Burst





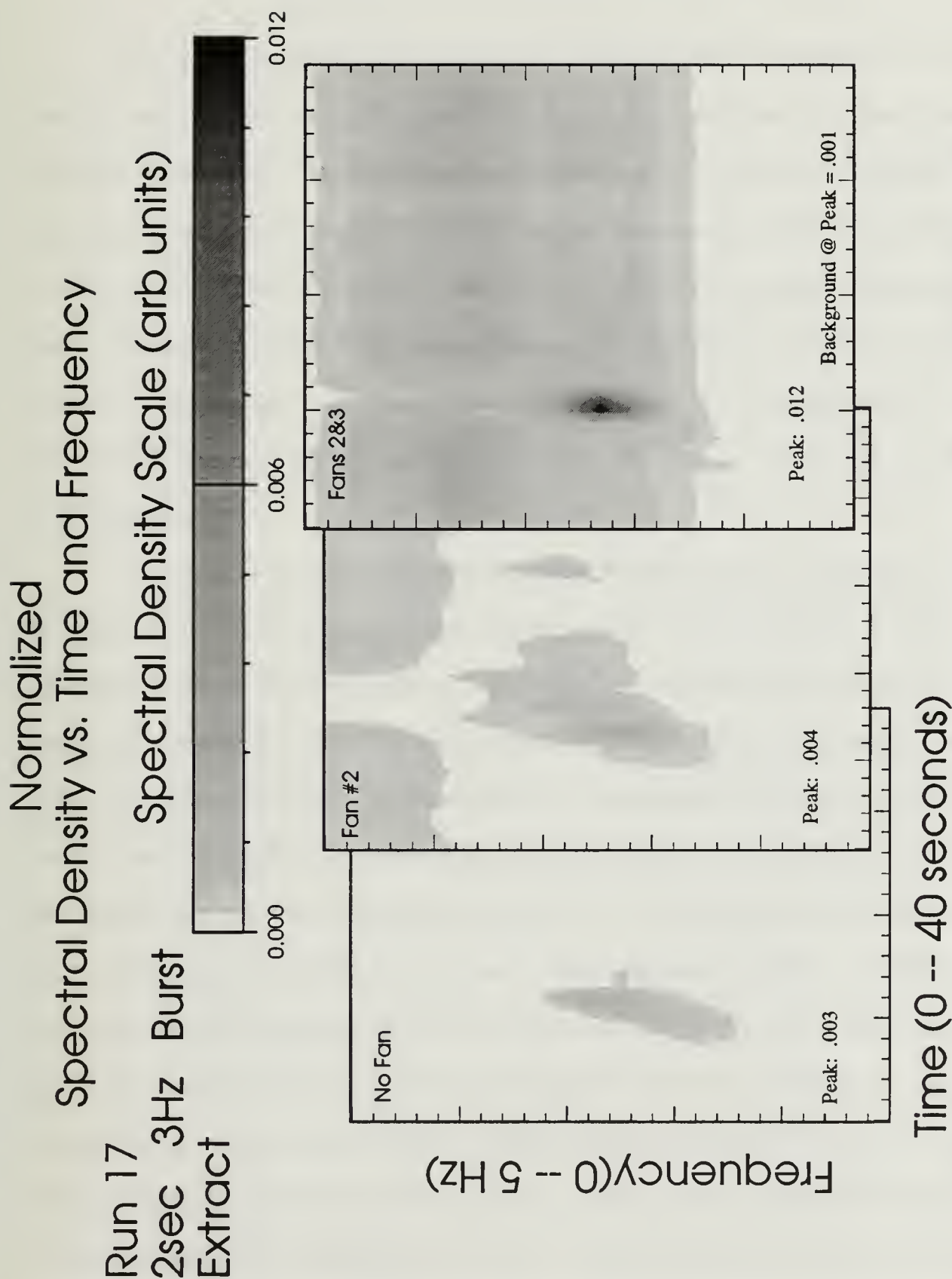


Figure 5.15 Relative Peak Spectral Density Increases as Function of Wind Speed for Narrowband Burst



## VI. CONCLUSIONS AND FUTURE WORK

The primary result of this experiment is the possible observation of a collective mode of sea state. The compelling reason to believe that it is indeed a collective mode is its nondispersive nature. The next significant aspect is that it appears to propagate at a speed independent of the input burst. The preceding observations may ultimately find application to sea state prediction in the ocean. They may also provide a transport mechanism for sea state, ultimately leading to an explanation of the uniformity of waves over the ocean surface. Perhaps most importantly, these observations may validate the use of condensed matter methods on ocean waves and allow the use of statistical mechanics in Oceanography.

In order to quantify the preceding observations and to positively confirm the presence of the collective mode, the experiment should be modified as follows. The launched pulse of waves should be originated at the opposite end of the tank, and thus propagate against the wind. The wind would attenuate the elementary surface waves, and only the collective mode would remain. The collective mode may appear as an enhancement rather than a depletion there because of the lack of a quiescent region between the paddle and the wind generated background. Additionally, the detector and data processing programs should be calibrated to give quantified results. Results in terms of energy could be compared with theory and provide another means of confirmation. With respect to data analysis, acquisition programs should be modified to allow more manipulation after the data is stored. In the frequency analysis of the wave height time series a Gabor Spectra could be implemented to obtain higher resolution in both time and frequency than the FFT method used above. Another prediction (Larrazza, 1992a) which could be verified is the spatial cross-correlation between two different probe positions. A

final recommendation for future experimentation involves launching the pulse into the open, anechoic area perpendicular to the wind driven waves in the tank and measuring the response at some distance midway down the tank from the open area. With the unusual boundary condition of waves coming into the long channel from the side, it is hoped that both enhancements and depletions of the background would be generated and propagate in both directions independent of the input burst, and perhaps a *transverse* collective mode (Larraza, 1992b; Larraza and Falkovich 1992) could be seen as well.

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